

Acknowledgements

This report was produced jointly by the Alternatives & Emissions Reduction Branch and Methane & Sequestration Branch of the U.S. EPA's Office of Air and Radiation, Office of Atmospheric Programs. Key staff from the Office of Air and Radiation include Dr. Stephen O. Andersen, Scott Bartos, Francisco de la Chesnaye, Eric Dolin, Rey Forte, David Godwin, Reid Harvey, Anhar Karimjee, Deborah Ottinger-Schaefer, and Sally Rand. Deanne Upson directed the final production of this report with support from Reid Harvey and oversight from Jeff Cohen and Dina Kruger.

The report would not have been complete without the efforts and contributions of many individuals and organizations. The following companies and organizations provided staff who reviewed a preliminary version of this report and provided useful comments: Alliance for Responsible Atmospheric Policy (with special thanks to Executive Director Dave Stirpe), Aeropres Corporation, 3M, Elf Atochem, Great Lakes Chemical Company, Trane Company, Air Products and Chemicals, Inc., Althoff Industries, Aluminum Company of America, AMAT, American Air Liquide, Ammonia Institute (IIAR), Air Conditioning and Refrigeration Institute (ARI), Association of Home Appliances Manufacturers (AHAM), Bonneville Power Administration, Cheminfo Services, Commercial Refrigerator Manufacturers Association, DuPont Fluoroproducts, Ecofys, Electric Power Research Institute (EPRI), Enviros March, European Aluminum Association (EAA), Foster Miller, GeoExchange, Global Centre for Process Change, Halons Alternatives Research Consortium (HARC), Hill Phoenix, Honeywell, Hughes Associates, Inc., Huntsman Polyurethanes, Hydro Magnesium, Hydro Light Metals, IBM, Intel Corporation, International Climate Change Partnership (ICCP), International Mobile Air Conditioning Association (IMACA), International Aluminum Institute, International Pharmaceutical Aerosol Consortium (IPAC), Litmas, Inc., Mitsubishi Electric, Mobile Air Conditioning Society (MACS), Motorola, Novellus Systems, Inc., Polyisocyanurate Insulation Manufacturers Association (PIMA), Raytheon Systems Company, Research Triangle Institute (RTI), International SEMATECH, Society of Automotive Engineers (SAE), Southern Company Service, Spray Polyurethane Alliance, Texas Instruments, The Aluminum Association, and Universal Technical Services. Although these organizations participated in the review of this analysis, these efforts do not constitute an endorsement of the results of this report or of any U.S. EPA policies and programs.

The staff of the Climate and Atmospheric Policy Practice at ICF Consulting deserves special recognition for their expertise, efforts in preparing many of the individual analyses, and for synthesizing this report.

Questions concerning this report should be directed to:

Jeff Cohen

Branch Chief

Alternatives & Emissions Reduction Branch

Global Programs Division

Office of Atmospheric Programs

U.S. Environmental Protection Agency

Mail Code 6202J

1200 Pennsylvania Avenue NW

Washington, DC 200000000

202-564-0135

202-565-2095 (fax)

cohen.jeff@epa.gov

Table of Contents

EXECUTIVE SUMMARY	ES-1
1. INTRODUCTION	1-1
1.1 Overview	1-1
1.2 Background	1-2
1.3 Historical and Baseline High GWP Gas Emissions Estimates	1-3
1.4 Economic Analysis of Options for Reducing Emissions of High GWP GASES	1-6
1.5 Marginal Abatement Curve	1-8
1.6 Uncertainties and Limitations	1-9
1.7 References	1-13
2. COST AND EMISSION REDUCTION ANALYSIS OF HFC-23 EMISSIONS FROM HCFC-22 PRODUCTION IN THE UNITED STATES	2-1
2.1 Introduction	2-1
2.2 Historical and Baseline HFC-23 Emission Estimates	2-2
2.3 HFC-23 Emission Reduction Opportunities	2-2
2.4 Cost Analysis	2-3
2.5 References	2-3
3. COST AND EMISSION REDUCTION ANALYSIS OF SF₆ EMISSIONS FROM ELECTRIC POWER TRANSMISSION AND DISTRIBUTION SYSTEMS IN THE UNITED STATES	3-1
3.1 Introduction	3-1
3.2 SF ₆ Baseline Emission Estimates	3-2
3.3 SF ₆ Emission Reduction Opportunities	3-3
3.4 Cost Analysis	3-3
3.5 References	3-4
4. COST AND EMISSION REDUCTION ANALYSIS OF SF₆ EMISSIONS FROM MAGNESIUM PRODUCTION AND PARTS CASTING IN THE UNITED STATES	4-1
4.1 Introduction	4-1
4.2 Historical and Baseline SF ₆ Emission Estimates	4-2
4.3 SF ₆ Emission Reduction Opportunities	4-2
4.4 Cost Analysis	4-5
4.5 References	4-6
5. COST AND EMISSION REDUCTION ANALYSIS OF PFC EMISSIONS FROM ALUMINUM SMELTERS IN THE UNITED STATES	5-1
5.1 Introduction	5-1
5.2 Historical and Baseline PFC Emission Estimates	5-2
5.3 PFC Emission Reduction Opportunities	5-3
5.4 Cost Analysis	5-4
5.4 References	5-6
6. COST AND EMISSION REDUCTION ANALYSIS OF PFC, HFC, AND SF₆ EMISSIONS FROM SEMICONDUCTOR MANUFACTURING IN THE UNITED STATES	6-1
6.1 Introduction	6-1
6.2 Historical and Baseline HFC, PFC, and SF ₆ Emission Estimates	6-2
6.3 HFC, PFC, and SF ₆ Emission Reduction Opportunities	6-3
6.4 Cost Analysis	6-5
6.5 References	6-7

7.	COST AND EMISSION REDUCTION ANALYSIS OF HFC EMISSIONS FROM REFRIGERATION AND AIR-CONDITIONING IN THE UNITED STATES	7-1
7.1	Introduction	7-1
7.2	Historical and Baseline HFC Emission Estimates	7-2
7.3	HFC Emission Reduction Opportunities	7-3
7.4	Cost Analysis	7-5
7.5	References	7-11
	APPENDIX 7.1. Refrigeration and Air-Conditioning End Uses	7-14
	APPENDIX 7.2. Alternative Refrigerants and HFC Emission Reduction Technologies	7-17
8.	COST AND EMISSION REDUCTION ANALYSIS OF HFC AND PFC/PFPE EMISSIONS FROM SOLVENTS IN THE UNITED STATES	8-1
8.1	Introduction	8-1
8.2	Historical and Baseline HFC and PFC/PFPE Emission Estimates	8-2
8.3	HFC and PFC/PFPE Emission Reduction Opportunities	8-3
8.4	Cost Analysis	8-4
8.5	References	8-6
	APPENDIX 8.1. Solvents End Uses, Alternatives, and Technologies	8-7
9.	COST AND EMISSION REDUCTION ANALYSIS OF HFC EMISSIONS FROM FOAMS IN THE UNITED STATES	9-1
9.1	Introduction	9-1
9.2	Historical and Baseline HFC Emission Estimates	9-2
9.3	Applicability of Non-HFC Blowing Agents	9-3
9.4	Cost Analysis	9-8
9.5	References	9-12
	APPENDIX 9.1: Description of HFC Emission Reduction Technologies and Practices	9-14
10.	COST AND EMISSION REDUCTION ANALYSIS OF HFC EMISSIONS FROM AEROSOLS IN THE UNITED STATES	10-1
10.1	Introduction	10-1
10.2	Historical and Baseline HFC Emission Estimates	10-2
10.3	HFC Emission Reduction Opportunities	10-3
10.4	Cost Analysis	10-4
10.5	References	10-6
11.	COST AND EMISSION REDUCTION ANALYSIS OF HFC AND PFC EMISSIONS FROM FIRE EXTINGUISHING IN THE UNITED STATES	11-1
11.1	Introduction	11-1
11.2	Historical and Baseline HFC and PFC Emission Estimates	11-3
11.3	HFC and PFC Emission Reduction Opportunities	11-3
11.4	Cost Analysis	11-4
11.5	References	11-5
	APPENDIX A. METHODOLOGY FOR ESTIMATING HFC AND PFC EMISSIONS FROM SUBSTITUTION OF OZONE DEPLETING SUBSTANCES	A-1
A.	Overview	A-1
B.	Emission Equations	A-2
C.	Model Output	A-6
	APPENDIX B. LIST OF ABBREVIATIONS	B-1

Executive Summary

The high global warming potential (GWP) gases include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆). These gases have become important to a wide array of industrial technologies and consumer products. HFCs in particular have become important to the safe and cost-effective phaseout of chlorofluorocarbons (CFCs), halons and other ozone depleting chemicals worldwide, and can also contribute to efforts to meet emission reduction targets in applications (e.g., foams, refrigeration and air-conditioning) where HFCs have an energy efficiency advantage. The sources of high GWP gas emissions include electric power distribution, refrigeration and air-conditioning, aluminum smelting, HCFC-22 production, aerosols, solvents, foams, fire extinguishing, semiconductor manufacturing, and magnesium production. Weighted by GWP, these gases accounted for about two percent of all U.S. greenhouse gas (GHG) emissions in 1999. However, by 2010, the level of these gases could increase to more than three times 1990 levels.¹ While most of the focus on GHG emission reduction opportunities has been on energy-related CO₂ emissions, reduced emissions of the high GWP gases can make a contribution to cost-effective GHG reductions.

The purpose of this report is to present EPA's estimates of the potential costs of reducing emissions of the high GWP gases in 2010, and to better characterize the role of the high GWP gases as part of a comprehensive GHG mitigation approach. A hypothetical "business-as-usual" forecast of future emissions has been developed under the assumption that no additional efforts will be made to reduce emissions of these gases. By using this forecast, the analysis is able to estimate the costs of innovative and voluntary reduction efforts undertaken by various industries. The analyses provided within this report can supplement carbon dioxide, nitrous oxide, and methane economic analyses to provide a broader understanding of the costs of a GHG mitigation strategy that covers all of these gases, and will help to identify opportunities to reduce such costs.

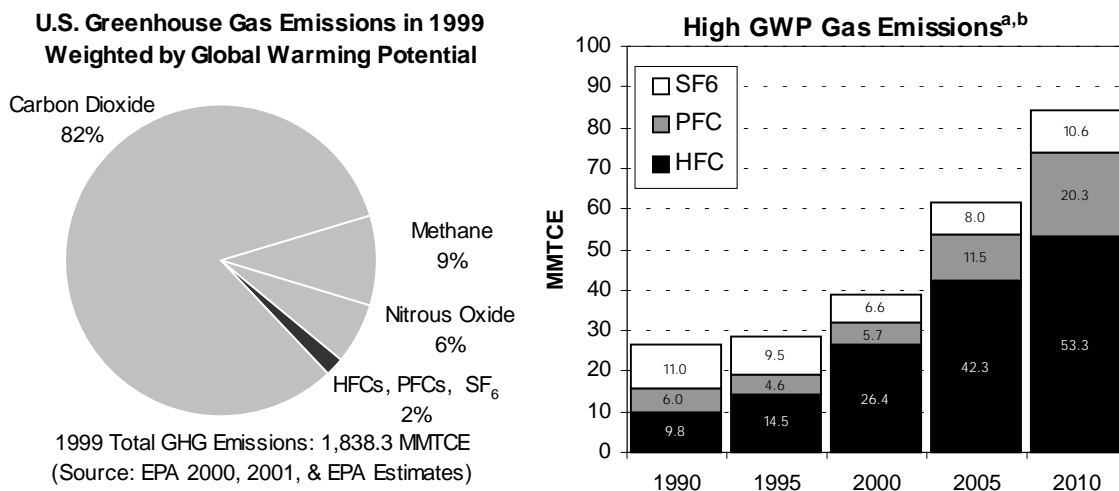
For each source of high GWP gas emissions, EPA has presented historical emissions and baseline forecasts of emissions. The report identifies various options for reducing emissions, based on literature review and consultation with industry. Where possible, the costs of implementing the options and the corresponding achievable emission reductions are estimated. Using discounted cash flow analysis, the report presents costs of emission reductions for each option on the basis of dollars per metric ton of carbon equivalent (\$/TCE). (Costs are presented in constant real year 2000 U.S. dollars for reductions in the year 2010.) After emission reduction options across all of the sources are ranked in ascending order by cost, a marginal abatement curve (MAC) showing the marginal emission reductions achievable at increasing costs of carbon (\$/TCE) is developed. The cost analysis incorporates indirect effects of direct emission reduction options where possible. The major findings of this report are summarized below.

Historical and Baseline High GWP Gas Emission Estimates

Historical and projected growth of high GWP gas emissions and their share of total U.S. GHG emissions are illustrated in Exhibit ES.1. All forecasts in this study assume a "business-as-usual" scenario under which no further voluntary action is expected. Under such a scenario, total U.S. emissions of high GWP gases are expected to reach 84.2 million metric tons of carbon equivalent (MMTCE) by 2010, a number 3.14 times 1990 levels. While high GWP gas emissions currently account for about two percent of the GWP-weighted U.S. GHG emissions, their use and emissions are by far the fastest growing of any GHG.

¹ Forecast emission estimates are based on a "business-as-usual" scenario, discussed briefly here and in more detail in the Introduction to the Report.

Exhibit ES.1: Contribution of High GWP Gas Emissions to U.S. Greenhouse Gas Emissions



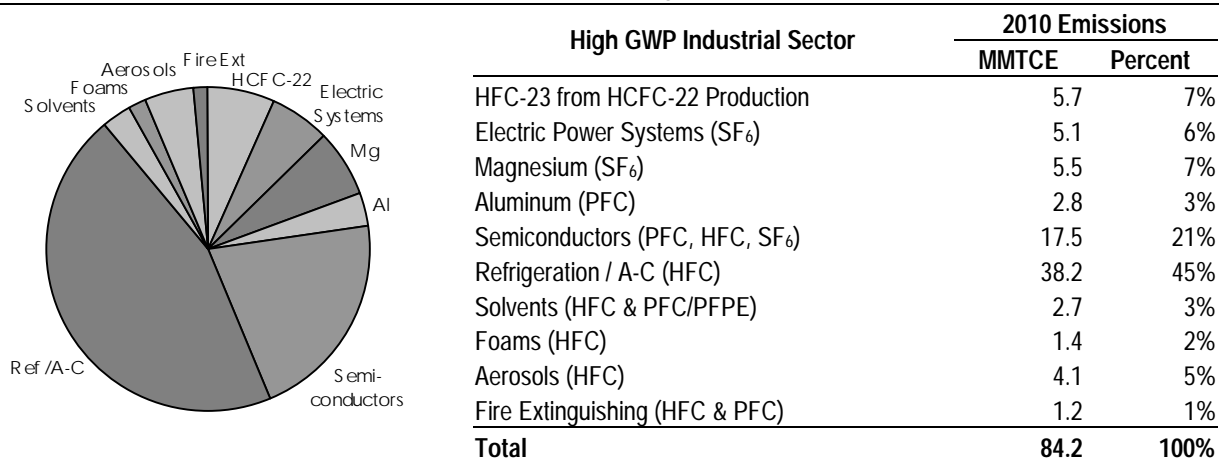
^a A fraction of the HFCs in this exhibit may also include PFC/PFPEs. This term is a proxy used to describe a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

^b Forecast emissions (years 2000, 2005, and 2010) are based on a "business-as-usual" scenario, assuming no further action.

Emissions of high GWP gases grew by 32 percent between 1990 and 1999. Most of this growth occurred as emissions of HFCs resulting from the increased use and production of substitutes for ozone depleting substances (ODS). The major sources that currently emit ODS substitutes include the solvents, foams, aerosols, fire extinguishing, and refrigeration/air-conditioning industries. Combined emissions from these sectors are estimated to reach as high as 47.6 (MMTCE) in 2010 if further reduction efforts are not made. This would represent a dramatic increase from the 0.3 MMTCE emitted in 1990.

The remaining emissions result from the aluminum, magnesium, HCFC-22, and semiconductor industries, as well as from electric power transmission and distribution systems. These together account for the remaining "business-as-usual" 2010 emissions estimate of 36.6 MMTCE. The relative contributions of each sector to overall 2010 high GWP gas emissions are shown in Exhibit ES.2.

Exhibit ES.2: Industrial Sectors and their Contributions to 2010 High GWP Gas Emissions



Note: Forecast emissions are based on a "business-as-usual" scenario, assuming no further action.

Historical factors that have driven growth in these industries generally include an expanding U.S. population, as well as an increase in per capita income and in standards of living; expanding markets and production rates, especially in sectors such as semiconductor manufacturing and magnesium production; and the increasing market penetration of ODS substitutes. Despite significant historical and projected growth in emissions, voluntary emission reduction efforts have the potential to result in substantial emission reductions. For instance, the semiconductor manufacturing and magnesium smelting industries have both made significant voluntary efforts, and emissions from aluminum smelting have fallen by more than 50 percent from 1990 levels under the EPA Voluntary Aluminum Industry Partnership (VAIP).

High GWP Gas Emission Reduction Opportunities

Most recent research and analyses of U.S. GHG emissions and reduction opportunities have focused on emissions of carbon dioxide (CO₂), which has historically accounted for more than 80 percent of greenhouse gas emissions (EPA, 2000). However, because high GWP gas use and emissions are a growing portion of GHGs in the United States, the opportunities presented here illustrate the potential for reducing overall GHG levels. The most promising opportunities to reduce high GWP gas emissions include:

- implementing new industrial processes that reduce emissions and improve efficiency;
- implementing better housekeeping practices;
- installing new, more efficient equipment with lower emission rates; and
- substituting other gases for high GWP gases in a variety of applications (where safety and performance requirements can be met).

The largest emission reduction potentials result from technological improvements, such as nitrogen trifluoride (NF₃) cleaning options and plasma abatement in the semiconductor manufacturing industry and thermal oxidation processes in the HCFC-22 chemical production industry. One of the least expensive reduction opportunities to implement, and one that is applicable to the most industries and processes, is the institution of better housekeeping practices that can reduce leaks of high GWP gases. Additionally, substituting other gases for high GWP gases is a viable option as long as environmental, health, safety, and performance requirements can be met.

Costs of Reducing Emissions

This report presents the results of discounted cash flow analyses that evaluate high GWP gas mitigation options available to each industry sector. Each option results in an emission reduction feasible at a corresponding carbon value (expressed as \$/TCE). Exhibit ES.3 illustrates feasible reductions by 2010 at certain carbon values. Individual emission reduction options are quantified for each industry using a four percent discount rate, and cumulatively lead to the aggregate U.S. MAC as shown in Exhibit ES.4. The cost analysis is conducted for the year 2010 with all values in constant real year 2000 dollars. Costs and emission reductions for options already required by law or expected under the baseline scenario are not included in these analyses. This 2010 MAC illustrates several key findings. For example, it is estimated that substantial emission reductions, 4.2 MMTCE, are achievable through reduction opportunities that are profitable (i.e., carbon values at or below \$0/TCE). This is possible where emission reduction options also improve efficiency or can be achieved by substituting less costly materials. Estimated emission reductions at a carbon value of \$20 per TCE are 28.6 MMTCE, while at a value of \$100 per TCE a reduction of over 36 MMTCE is attainable.

In general, the curve becomes increasingly inelastic at values above \$40/TCE, where the sum of emissions avoided becomes increasingly less responsive to higher carbon values. Exhibit ES.5 contains the data for all the reduction options that contribute to the MAC. Costs vary among the viable options from those that incur none at all (and in some cases result in savings) to those that present costs of more than \$150 per TCE reduced. The MAC and data are also presented using an eight percent discount rate, in Exhibits ES.6 and ES.7.

Exhibit ES.3: U.S. 2010 Baseline High GWP Gas Emissions and Potential Reductions (at a 4% discount rate)

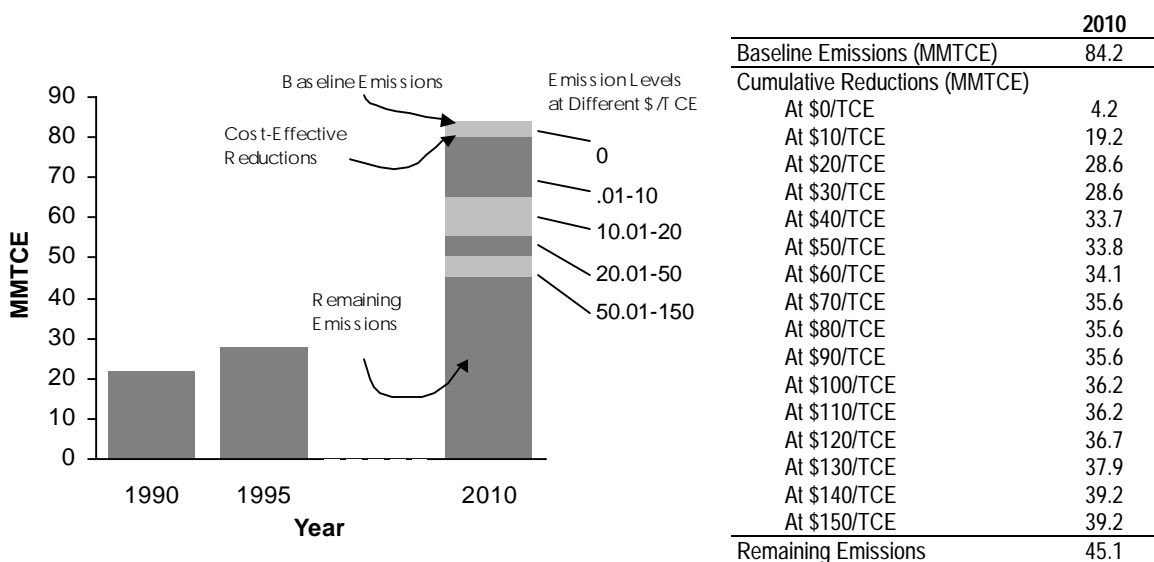


Exhibit ES.4: Marginal Abatement Curve for U.S. High GWP Gas Emissions in 2010 (at a 4% discount rate)

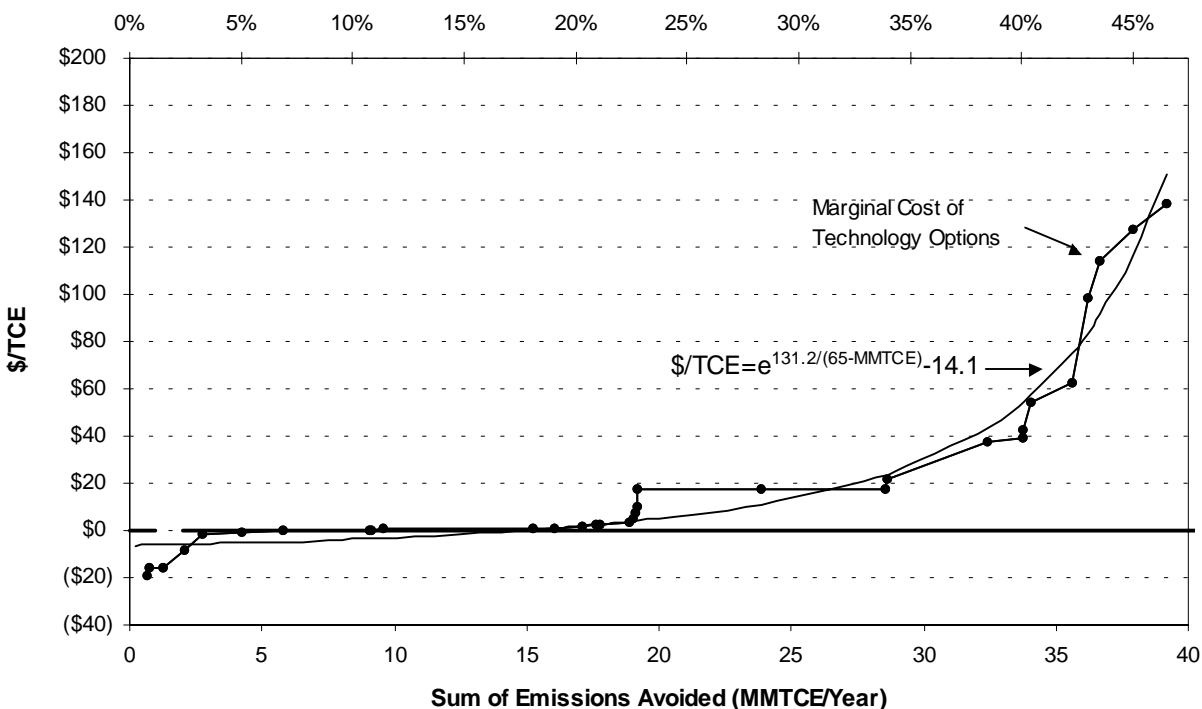


Exhibit ES.5: Composite Marginal Discount Curve Schedule of Options for 2010 (at a 4% discount rate)

#	Source	Activity	Cost (\$/TCE)	Emission Reduction (MMTCE)	Sum of Reduction (MMTCE)	Percent Reduction from 2010 Baseline
1	Aerosols	Hydrocarbon Aerosol Propellants	\$ (20.35)	0.2	0.2	0%
2	Aerosols	Not-in-kind Alternatives	\$ (19.15)	0.5	0.7	1%
3	Fire Extinguishing	Water Mist	\$ (16.19)	<0.05	0.7	1%
4	Foams	PU Spray Foams - Replace HFC-245fa/CO ₂ (water) with hydrocarbons	\$ (15.70)	0.5	1.2	1%
5	Aerosols	Switching to HFC-152a	\$ (8.14)	0.8	2.1	2%
6	Magnesium Smelting	Good Housekeeping	\$ (1.91)	0.7	2.8	3%
7	Magnesium Smelting	SF ₆ Capture/Recycling	\$ (0.90)	1.5	4.2	5%
8	Refrigeration/AC	Replace DX with Distributed System	\$ 0.02	1.5	5.8	7%
9	Magnesium Smelting	SO ₂ Replacement	\$ 0.25	3.3	9.1	11%
10	Aluminum Smelting	Retrofit-Minor: VSS	\$ 0.27	<0.05	9.1	11%
11	Aluminum Smelting	Retrofit-Major: SWPB	\$ 0.43	0.4	9.6	11%
12	HCFC-22 Production	Thermal Oxidation	\$ 0.64	5.7	15.3	18%
13	Solvents	Alternative Solvents	\$ 0.88	0.8	16.1	19%
14	Electric Utilities	Leak Detection and Repair	\$ 1.62	1.0	17.1	20%
15	Electric Utilities	Recycling Equipment	\$ 2.30	0.5	17.6	21%
16	Aluminum Smelting	Retrofit-Major: CWPB	\$ 2.50	0.2	17.8	21%
17	Refrigeration/AC	Leak Reduction Options	\$ 3.58	1.2	18.9	22%
18	Aluminum Smelting	Retrofit-Major: HSS	\$ 5.23	0.1	19.1	23%
19	Aluminum Smelting	Retrofit-Major: VSS	\$ 7.25	0.1	19.1	23%
20	Solvents	NIK Semi-Aqueous	\$ 9.63	<0.05	19.2	23%
21	Foams	PU Appliance Foams - Replace HFC-134a with cyclopentane	\$ 17.18	<0.05	19.2	23%
22	Semiconductor Manufacturing	NF ₃ Drop-In	\$ 17.51	4.7	23.9	28%
23	Semiconductor Manufacturing	NF ₃ Remote Cleaning	\$ 17.51	4.7	28.6	34%
24	Solvents	NIK Aqueous	\$ 21.57	<0.05	28.6	34%
25	Semiconductor Manufacturing	Plasma Abatement	\$ 37.87	3.8	32.4	38%
26	Semiconductor Manufacturing	Capture/Recycling	\$ 39.58	1.3	33.7	40%
27	Solvents	Retrofit Options	\$ 42.45	<0.05	33.8	40%
28	Fire Extinguishing	Inert Gas Systems	\$ 53.86	0.3	34.1	40%
29	Refrigeration/AC	HFC Secondary Loop Systems	\$ 62.57	1.5	35.6	42%
30	Refrigeration/AC	Ammonia Secondary Loop Systems	\$ 98.61	0.6	36.2	43%
31	Foams	PU Spray Foams - Replace HFC-245fa/CO ₂ (water) with CO ₂ (water)	\$ 114.09	0.5	36.7	44%
32	Semiconductor Manufacturing	Catalytic Destruction	\$ 127.29	1.2	37.9	45%
33	Semiconductor Manufacturing	Thermal Destruction	\$ 138.61	1.3	39.2	46%

Exhibit ES.6: U.S. High GWP Gas Marginal Abatement Curve for 2010 (at an 8% discount rate)

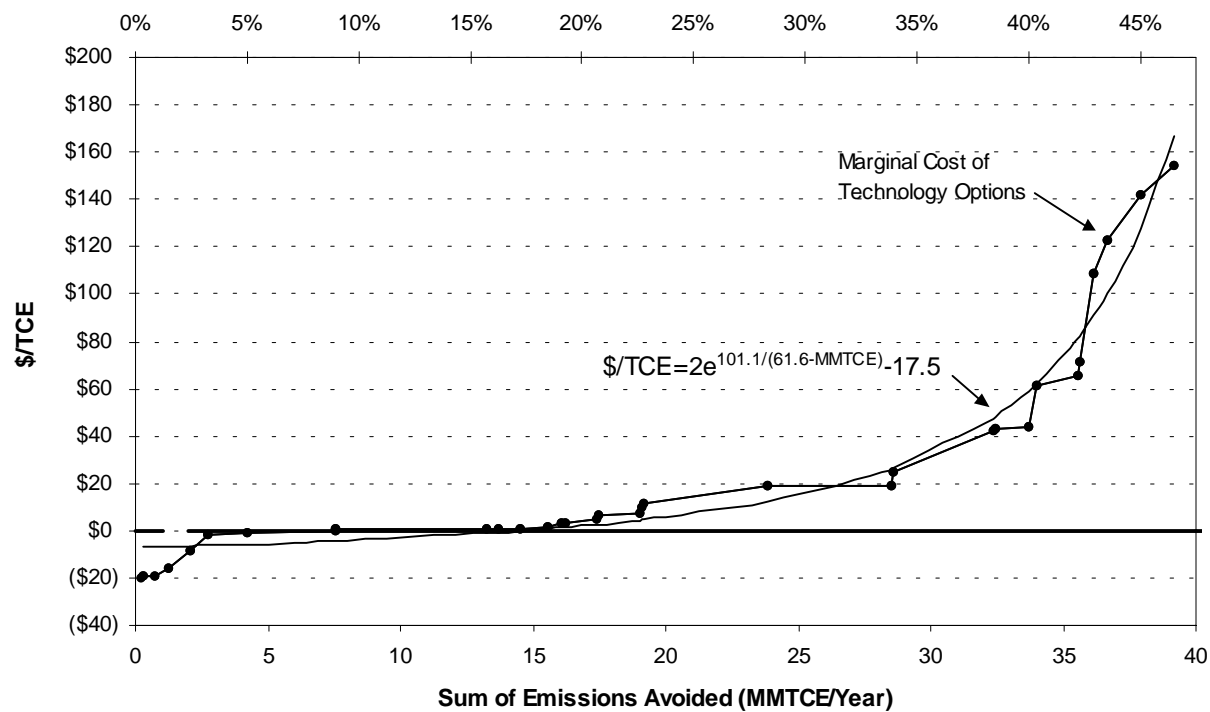


Exhibit ES.7: Composite Marginal Discount Curve Schedule of Options for 2010 (at an 8% discount rate)

#	Source	Activity	Cost (\$/TCE)	Emission Reduction (MMTCE)	Sum of Reduction (MMTCE)	Percent Reduction from 2010 Baseline
1	Aerosols	Hydrocarbon Aerosol Propellants	\$ (20.32)	0.2	0.2	0%
2	Fire Extinguishing	Water Mist	\$ (19.42)	<0.05	0.3	0%
3	Aerosols	Not-in-kind Alternatives	\$ (19.12)	0.5	0.7	1%
4	Foams	PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with hydrocarbons	\$ (15.64)	0.5	1.2	1%
5	Aerosols	Switching to HFC-152a	\$ (8.09)	0.8	2.1	2%
6	Magnesium Smelting	Good Housekeeping	\$ (1.91)	0.7	2.8	3%
7	Magnesium Smelting	SF ₆ Capture/Recycling	\$ (0.89)	1.5	4.2	5%
8	Magnesium Smelting	SO ₂ Replacement	\$ 0.24	3.3	7.5	9%
9	Aluminum Smelting	Retrofit-Minor: VSS	\$ 0.54	<0.05	7.6	9%
10	HCFC-22 Production	Thermal Oxidation	\$ 0.73	5.7	13.3	16%
11	Aluminum Smelting	Retrofit-Major: SWPB	\$ 0.77	0.4	13.7	16%
12	Solvents	Alternative Solvents	\$ 0.88	0.8	14.5	17%
13	Electric Utilities	Leak Detection and Repair	\$ 1.62	1.0	15.5	18%
14	Electric Utilities	Recycling Equipment	\$ 3.28	0.5	16.1	19%
15	Aluminum Smelting	Retrofit-Major: CWPB	\$ 3.30	0.2	16.2	19%
16	Refrigeration/AC	Leak Reduction Options	\$ 5.08	1.2	17.4	21%
17	Aluminum Smelting	Retrofit-Major: HSS	\$ 6.82	0.1	17.5	21%
18	Refrigeration/AC	Replace DX with Distributed System	\$ 7.21	1.5	19.1	23%
19	Aluminum Smelting	Retrofit-Major: VSS	\$ 9.58	0.1	19.1	23%
20	Solvents	NIK Semi-Aqueous	\$ 11.55	<0.05	19.2	23%
21	Semiconductor Manufacturing	NF ₃ Drop-In	\$ 18.57	4.7	23.9	28%
22	Semiconductor Manufacturing	NF ₃ Remote Cleaning	\$ 18.57	4.7	28.6	34%
23	Solvents	NIK Aqueous	\$ 25.02	<0.05	28.6	34%
24	Semiconductor Manufacturing	Plasma Abatement	\$ 41.95	3.8	32.4	38%
25	Foams	PU Appliance Foams - Replace HFC-134a with cyclopentane	\$ 43.25	<0.05	32.4	38%
26	Semiconductor Manufacturing	Capture/Recycling	\$ 43.99	1.3	33.7	40%
27	Fire Extinguishing	Inert Gas Systems	\$ 61.44	0.3	34.0	40%
28	Refrigeration/AC	HFC Secondary Loop Systems	\$ 65.30	1.5	35.6	42%
29	Solvents	Retrofit Options	\$ 71.24	<0.05	35.6	42%
30	Refrigeration/AC	Ammonia Secondary Loop Systems	\$ 108.67	0.6	36.2	43%
31	Foams	PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with CO ₂ (water)	\$ 122.52	0.5	36.7	44%
32	Semiconductor Manufacturing	Catalytic Destruction	\$ 141.93	1.2	37.9	45%
33	Semiconductor Manufacturing	Thermal Destruction	\$ 154.54	1.3	39.2	46%

References

EPA. 2000. *Inventory of Greenhouse Gas Emissions and Sinks 1990-1998*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC; EPA 236-R-00-001. (Available on the Internet at <http://www.epa.gov/globalwarming/emissions/national/download.htm>).

EPA. 2001. *Inventory of Greenhouse Gas Emissions and Sinks 1990-1999*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC; EPA 236-R-01-001. (Available on the Internet at <http://www.epa.gov/globalwarming/emissions/national/download.htm>).

1. Introduction

1.1 Overview

Since 1990, EPA has sought to reduce greenhouse gas (GHG) emissions through a variety of partnership programs that promote the use of energy efficient technologies and management practices. Most of the focus on reduction opportunities has been on energy-related carbon dioxide (CO₂) emissions, which currently account for about 81 percent of the total U.S. GHG emissions (EPA, 2001).¹ However, reduced emissions of the non-CO₂ GHGs—methane, nitrous oxide, and the high global warming potential (GWP) gases hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride (HFCs, PFCs, and SF₆)—can also make a contribution to cost-effective GHG emission reductions (see, for example, Hayhoe *et al.*, 1999; Reilly *et al.*, 1999a and 1999b). This report has been developed, in part, to better characterize the role of the high GWP gases as part of a comprehensive GHG mitigation approach. To this end, this report develops marginal abatement cost data that can be used in macroeconomic analyses of climate change mitigation strategies.

This report has three objectives. First, it presents EPA's current forecasts of U.S. high GWP gas emissions through 2010 under a "business-as-usual" scenario that assumes no further actions are taken to reduce emissions. Second, the report uses available cost and technical data to describe those technologies and practices that can reduce these emissions from the major emission sources, some of which are expected to be voluntarily adopted by industry. Third, the report estimates the costs of reducing high GWP gas emissions for each major source and assembles these costs into a marginal abatement curve (MAC) that shows the total emission reductions achievable at increasing monetary values of carbon, for the year 2010. This introduction describes the general methodological issues for estimating the MAC.

The remainder of this report is organized into the following chapters. Each chapter corresponds to one of the major source categories of high GWP gases:

- Chapter 2. HFC-23 Emissions from HCFC-22 Production
- Chapter 3. SF₆ Emissions from Electric Power Transmission and Distribution Systems
- Chapter 4. SF₆ Emissions from Magnesium Production and Parts Casting
- Chapter 5. PFC Emissions from Aluminum Smelters
- Chapter 6. PFC, HFC, and SF₆ Emissions from Semiconductor Manufacturing
- Chapter 7. HFC Emissions from Refrigeration and Air-Conditioning
- Chapter 8. HFC and PFC/PFPE Emissions from Solvents
- Chapter 9. HFC Emissions from Foams
- Chapter 10. HFC Emissions from Aerosols
- Chapter 11. HFC and PFC Emissions from Fire Extinguishing

¹ Emissions are weighted by 100-year global warming potentials (GWPs).

Each chapter presents the following information:

- *Baseline Emissions of High GWP Gases.* The source of the emissions in the United States is summarized, followed by a baseline forecast of U.S. emissions from that source through 2010. This baseline is estimated under a “business-as-usual” case scenario and assumes that no further voluntary actions are taken to reduce emissions.
- *High GWP Gas Emission Reduction Options and Associated Costs.* Each chapter summarizes the known technologies and practices for reducing the emissions from the source and estimates a cost for reducing emissions in terms of dollars per metric ton of carbon equivalent (\$/TCE).

The framework for this analysis is national in scope, consistent with the intent to develop inputs useful for macroeconomic studies of potential climate change policy. Given this broad view, this report does not present highly detailed analyses of the individual sources of high GWP gas emissions, nor does it attempt to comprehensively evaluate the comparative advantages or technical challenges of alternative technologies in specific industry sectors. Rather, EPA has largely relied on available literature and expert review to identify possible options in the different industries that use high GWP gases to provide credible estimates of emissions and costs under alternative scenarios. Where detailed data and information have been available, as is the case for the refrigeration and air-conditioning sector, a more detailed treatment is presented. EPA intends to update this analysis over time as more information is developed.

1.2 Background

The use of hydrofluorocarbons (HFCs) has allowed the rapid phaseout of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons in the U.S. and other countries for applications where other alternatives were not available. HFCs have generally been selected for applications where they provide superior technical (reliability) or safety (low toxicity and flammability) performance. In many cases, HFCs provide equal or better energy efficiency compared to other available alternatives, thereby

Exhibit 1.1: Major High GWP Gases in the United States (100-year GWPs)^a

Gas	GWP	Atmospheric Lifetime (yrs)	Source of Emissions
HFC-23	11,700	264	HCFC-22 Production, Fire Extinguishing Equipment, Aerosols, Semiconductor Manufacture
HFC-43-10mee	1,300	17.1	Solvents
HFC-125	2,800	32.6	Refrigeration/Air-Conditioning
HFC-134a	1,300	14.6	Refrigeration/Air-Conditioning, Aerosols, Foams
HFC-143a	3,800	48.3	Refrigeration/Air-Conditioning
HFC-152a	140	1.5	Refrigeration/Air-Conditioning, Aerosols, Foams
HFC-227ea	2,900	36.5	Aerosols, Fire Extinguishing Equipment
HFC-236fa	6,300	209	Refrigeration/Air-Conditioning, Fire Extinguishing
SF ₆	23,900	3,200	Electric Utilities; Magnesium Production; Semiconductor Manufacture
PFCs (primarily CF ₄ and C ₂ F ₆)	6,500 – 9,200	2,600-50,000	Aluminum Smelting, Semiconductor Manufacture, Fire Extinguishing
PFC/PFPEs ^b	7,400	3,200	Solvents

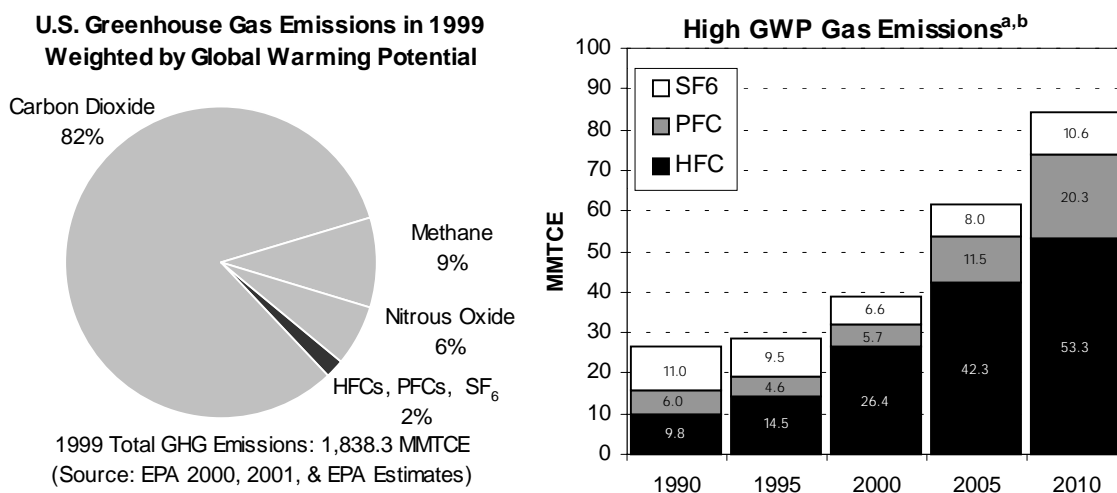
^a Note that this table lists major commercial gases and sources; other minor gases and uses such as lab applications are not listed here. The GWP and atmospheric lifetimes are taken from Climate Change 1995, the IPCC Second Assessment Report (Schimel *et al.*, 1995).

^b PFC/PFPEs are a diverse collection of PFCs and perfluoropolyethers (PFPEs) used as solvents.

reducing long-term environmental impacts. HFCs are expected to replace a significant portion of past and current demand for CFCs and HCFCs in insulating foams, refrigeration and air-conditioning, propellants used in metered dose inhalers, and other applications. HFCs are also becoming important substitutes for halons used in specialized fire protection equipment. Perfluorocarbons (PFCs) have been introduced in a small number of applications as alternatives to ozone depleting substances (ODS), specifically in very limited refrigeration and fire protection applications, and as important agents in semiconductor manufacture. However, these gases, along with SF₆, which is used as a dielectric or cover gas in industrial applications, are many times more effective (on a per ton basis) than CO₂ in trapping heat in the atmosphere. The GWPs of these gases range from 140 to over 23,900 times the global warming capability of CO₂, and in some cases these gases remain in the atmosphere for hundreds or thousands of years (see Exhibit 1.1). However, the most widely used high GWP gas is HFC-134a, which has a shorter lifetime of about 15 years.

Although these high GWP gases currently account for about two percent of the GWP-weighted U.S. greenhouse gas emissions, their use and emissions are growing (EPA, 2001). Exhibit 1.2 shows that by 2010, high GWP gas emissions could increase to over three times 1990 levels if no further reduction actions are taken. This forecast is based on a “business-as-usual” case, without taking into account industry’s voluntary efforts to reduce emissions. Because of voluntary actions underway or planned by several industry sectors, actual emission growth is expected to be smaller.

Exhibit 1.2: Contribution of High GWP Gas Emissions to U.S. Greenhouse Gas Emissions



^a A fraction of the HFCs in this exhibit may also include PFC/PFPEs. This term is a proxy used to describe a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

^b Forecast emissions (years 2000, 2005, and 2010) are based on a “business-as-usual” scenario, assuming no further action.

1.3 Historical and Baseline High GWP Gas Emissions Estimates

The methodology for estimating current and future emissions of high GWP gases varies with the source, as described below.

ODS Substitutes. EPA uses a detailed vintaging model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes, principally HFCs and PFCs. The Vintaging Model estimates ODS and ODS substitute use in the United States based on estimates of the quantity of equipment or products sold each year containing these chemicals, and the amount of the chemical

required to make or maintain equipment and products over time. Emissions for each end use—including refrigeration and air-conditioning, solvents, foams, aerosols, and fire extinguishing—are estimated by applying annual leak rates and release profiles. The model aggregates data for more than 40 end uses, keeping track of equipment vintages to estimate annual use and emissions of each compound. Appendix A presents a detailed description of the Vintaging Model.

Other Industrial Sources. Emissions of the high GWP gases from other industrial sources—PFCs, HFCs and SF₆ from semiconductor manufacturing; PFCs from aluminum production; SF₆ from the magnesium and electric power systems sectors; and HFC-23 from HCFC-22 production—are estimated from production characteristics of the end use that emits each gas. For some production-related industrial processes, an emission factor is applied that relates the high GWP gas emissions to the output of the process (e.g., HCFC-22 production drives HFC-23 emission estimates and magnesium production determines some SF₆ emissions). For other industries, emissions are related to specific characteristics of the production process. For example, PFC emissions from transitory “anode effects” in aluminum smelting depend on the frequency and duration of the process characteristic that produces this gas. For SF₆ used as insulation in electrical transmission and distribution systems, emissions are more directly related to equipment characteristics (e.g., age and size) and sales of SF₆ than to electricity production.

Exhibit 1.3 presents the emission estimates of high GWP gases by source for the years 1990 through 1999. As the exhibit illustrates, there has been a rise in ODS substitute emissions since 1990 and steady growth in emissions from most of the remaining high GWP sources. In some cases, declines in emissions are a result of voluntary emission reduction efforts by industry undertaken through EPA partnership programs under the Climate Change Action Plan (CCAP). For example, under the Voluntary Aluminum Industrial Partnership (VAIP), emissions of PFCs from aluminum smelting have fallen by over 50 percent from 1990 levels.

Exhibit 1.3: Historical U.S. High GWP Gas Emissions (MMTCE)

Source of High GWP Gases	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
HFC-23 from HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5	8.2	10.9	8.3
Electric Power Systems (SF ₆)	9.5	9.9	9.2	10.4	9.5	8.0	8.1	7.4	6.1	4.7
Magnesium (SF ₆)	1.5	1.5	1.5	1.5	1.4	1.5	1.5	2.0	1.7	1.7
Aluminum (PFCs)	5.3	4.7	4.4	3.8	3.1	3.1	3.2	3.0	2.8	2.7
Semiconductors (PFCs, HFCs & SF ₆)	0.8	0.8	0.8	1.0	1.2	1.5	1.9	1.9	1.9	1.9
Total of ODS Substitutes	0.3	0.4	0.6	1.7	3.0	7.1	9.9	12.1	14.2	16.2
TOTAL	26.8	25.6	26.0	27.1	26.8	28.6	33.2	34.7	37.6	35.5

Source: EPA 2000, 2001, and EPA estimates.

Notes:

The ODS substitutes include the refrigeration and air-conditioning, solvents, foams, aerosols, and fire extinguishing industries.

Sums might not add to total due to rounding.

The baseline forecast of high GWP gas emissions for the years 2000-2010 is presented in Exhibit 1.4. Overall, the exhibit shows that emissions could be expected to grow substantially over the forecast period, primarily from the use of ODS substitutes. The introduction of ODS substitutes to the refrigeration and air-conditioning sector is the major driver of this growth, primarily because the sector is so large. The only sector where emissions decline over the forecast period is HFC-23 emissions from HCFC-22 manufacturing, because the phaseout of certain HCFC uses in the United States is expected to impact HCFC-22 demand.

These projected baseline emission estimates do not include further reductions that are expected to result from implementation of continued voluntary actions across these industries. As a result, actual future

emissions are expected to be lower than this analytical baseline. Because these programs are voluntary, industry decisions to pursue reductions will depend on the cost-effectiveness of the reduction options. A major purpose of this report is to estimate the cost-effectiveness of various emission reduction options and to determine the quantity of future emission reductions achievable at different values of carbon.

Exhibit 1.4: Baseline U.S. High GWP Gas Emissions (MMTCE)

Sources of High GWP Gases	Forecast Emissions		
	2000	2005	2010
HFC-23 from HCFC-22 Production	8.2	7.4	5.7
Electric Power Systems (SF ₆)	4.7	4.9	5.1
Magnesium (SF ₆)	1.8	3.1	5.5
Aluminum (PFCs)	2.6	2.8	2.8
Semiconductors (PFCs, HFCs & SF ₆)	3.1	8.7	17.5
ODS Substitutes	18.2	34.9	47.6
TOTAL	38.7	61.8	84.2

Notes:

Forecast assumes a "business-as-usual" scenario under which no further industry action occurs.

The emissions forecast includes only direct emissions. Indirect emissions—those that result from changes in energy efficiency after a reduction option has been implemented—are not included. A more detailed discussion of indirect emissions appears in the Life Cycle Climate Performance section.

Voluntary Program Reductions

Under the Climate Change Action Plan, voluntary programs are aimed at achieving cost-effective emission reductions by overcoming various informational, regulatory, financial, and institutional barriers. CCAP was initiated in 1993 and incorporates over forty voluntary industry-government cooperative programs to reduce greenhouse gas emissions. For this analysis, five voluntary programs are considered, all of which target reductions of high GWP gas emissions. The Voluntary Aluminum Industrial Partnership promotes reductions of PFCs from primary aluminum production processes. Similarly, the partnership with HCFC-22 producers commits manufacturers to voluntarily reduce HFC-23 emissions. The remaining three programs are aimed at reducing emissions of PFCs and HFCs from semiconductor production, SF₆ in electrical transmission and distribution systems, and SF₆ in magnesium casting.

Aggregate targets for reducing high GWP gas emissions under CCAP programs include the following: reducing emissions by 13.7 MMTCE by the year 2000 and by 17.4 MMTCE by 2010 (DOS, 1997). Anticipated CCAP emission reductions are not included in the baseline emissions presented in this analysis for the years 2000 through 2010.

In addition to voluntary CCAP programs, Section 612 of the Clean Air Act (CAA) authorized EPA to establish the Significant New Alternatives Policy (SNAP) program. SNAP lists acceptable and unacceptable substitutes for Class I ODS (CFCs, halons, carbon tetrachloride, methyl chloroform, methyl bromide, and hydrobromofluorocarbons (HBFCs)) and Class II ODS (HCFCs). Actions from SNAP are expected to result in emission reductions of approximately 43 MMTCE in 2010. Because these emission reductions are required by regulations promulgated under the CAA, baseline emissions of ODS substitutes already include these reductions.

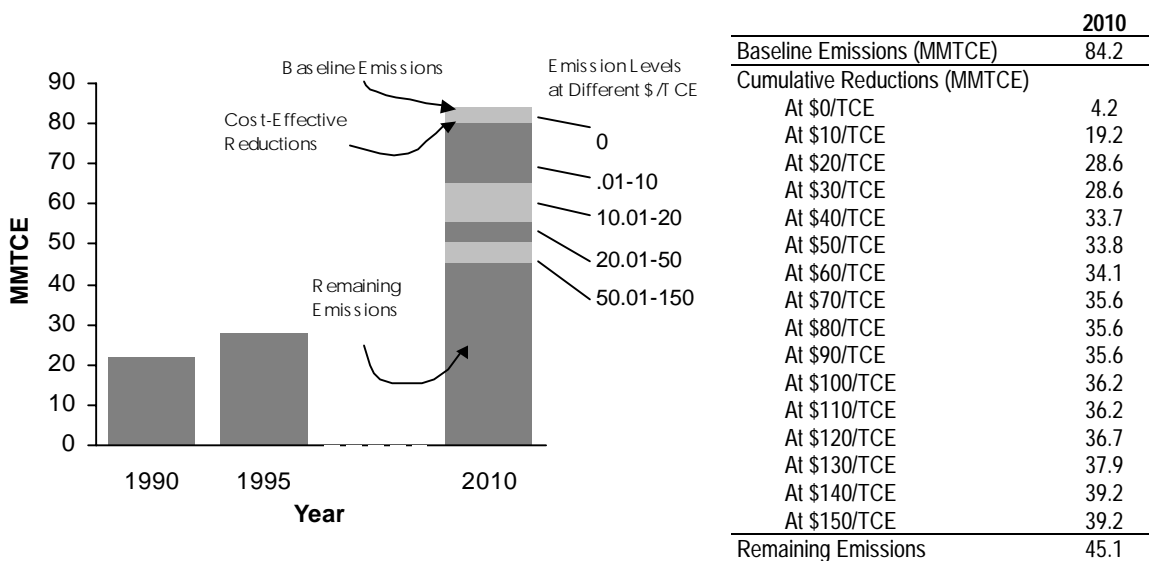
1.4 Economic Analysis of Options for Reducing Emissions of High GWP Gases

Options for reducing emissions of high GWP gases are described in the following chapters for each major source. Where possible, the options are described in terms of the cost of implementation and the reduced emissions that can be achieved. As discussed, costs and emission reductions for options already required by law or expected due to voluntary partnership programs are not included under the baseline. The reduction options assessed in this report were identified from various reports and literature on emission reductions, industry publications, and industry contacts. To date, the most promising options to reduce high GWP gas emissions include:

- implementing new industrial processes that reduce emissions and improve efficiency,
- implementing better housekeeping practices to reduce leaks of high GWP gases,
- installing new, more efficient equipment with lower emission rates, and
- substituting other gases for high GWP gases in a variety of applications, where safety and performance requirements can be met.

This report uses discounted cash flow analysis to estimate the cost of achieving reductions for each technology or practice for each emission source. Costs are presented in dollars per metric ton of carbon equivalent (\$/TCE). Discounted cash flow analysis reflects the decision-making process that manufacturers use when considering investments in emission reduction practices. This approach is the same method EPA has used in developing MACs for methane emissions (see EPA, 1999).

Exhibit 1.5: U.S. Historical and Baseline Emissions and Potential Reductions (at a 4% discount rate)



The costs of reducing emissions have been delineated as both capital investment and operating and maintenance (O&M) costs. In most cases, data on these costs were available; where data were not available, EPA has summarized the options qualitatively.

The benefits calculations incorporate two elements of value. The first element is the value of the savings that are achieved by reducing emissions of a product or by improving process efficiency. For example,

where SF₆ emissions can be reduced by substituting other less expensive gases, the difference in the price of SF₆ and the substitute is counted as a benefit. Where SF₆ emissions are reduced through process improvements, the benefit is the avoided cost of replacing the SF₆ that would have been emitted. In some cases, benefits occur with process efficiencies that lower other O&M costs. The second element of value is the implied value of carbon. This is incorporated in the following way: the discounted cash flow analysis solves for the value of benefits necessary to equal the costs of undertaking the investment. Stated in another way, the analysis solves for the level of benefits needed to yield a net present value (NPV) of zero for the stream of benefits minus costs. Where the level of benefit necessary is in excess of the O&M savings discussed above, the increment needed to yield an NPV of zero is deemed to be the price of carbon. For some options, the price of carbon can be zero or even negative. For most options, however, some value of carbon must be added in order to make the investment economically viable. In this analysis, only options that cost less than \$200 per metric ton of carbon equivalent are included in the MAC.

Discounting

Benefits and costs are discounted over the planning horizon. EPA has used two discount rates. A four percent rate is used for comparison with similar studies by other countries. An eight percent discount rate is also used to more closely approximate private decision-making and for comparison with EPA's MAC for methane emissions (EPA, 1999). All costs and benefits are presented in real year 2000 dollars for emission reductions undertaken in the year 2010.

There is a substantial volume of economic literature about the appropriate discount rate to use in discounting public and private sector benefits and costs over time. The U.S. Office of Management and Budget (OMB) issued guidelines on this topic that suggest using "the opportunity cost of capital, as measured by the before-tax rate of return to incremental private investment" (e.g., about seven percent) (OMB, 2000). In addition, OMB encourages sensitivity analyses using the "social rate of time preference," for which many analysts use the average rate on long-term treasury bonds (about three percent in recent years). Thus, the four and eight percent discount rates used in this analysis are slightly higher and thus more conservative than those suggested in the OMB guidelines.

Life Cycle Climate Performance

The analyses in this report incorporate the "life cycle climate performance" (LCCP) of emission reduction options. The concept of LCCP is based on the fact that replacing high GWP gases in some applications may lead to greater emissions of GHGs elsewhere in the economy. The net effect of some actions to lower high GWP gas emissions, therefore, could increase emissions overall, or at least reduce the net benefits. For example, substitutions for high GWP gases in various refrigeration or air-conditioning systems or insulating foam manufacturing could, in some cases, result in less efficient performance and higher energy use. This in turn would lead to greater energy consumption and higher CO₂ emissions from electricity generation. In some cases, the increased energy consumption outweighs the emission reduction that would be expected by replacing a high GWP gas with one that has no or very low GWP. In other cases, however, the LCCP is improved, such as when alternatives to ODS substitutes are both more efficient and have lower GWPs. Evaluating the LCCP of an option, therefore, involves considering the net of the direct (reduction of high GWP gas) and indirect effects (increase of other greenhouse gases) of that option. Where possible, the LCCP analysis also incorporates losses incurred during the manufacture of the chemical and ultimate disposal of equipment.

This issue is most apparent when evaluating reductions of the high GWP ODS substitutes in the refrigeration and air-conditioning sector and in foams manufacturing. Within the chapters that describe these sectors, the LCCP of each option has been incorporated into the option analyses, where possible. As described in the chapters, LCCP has been incorporated into the analysis by including the additional

costs for greater electricity consumption and reduced benefits that reflect the net of direct and indirect emission effects. It should be noted that some components of the LCCP analysis—such as energy costs and variability in emissions (CO₂) per kilowatt-hour—do vary across the residential, commercial, and industrial sectors. To be conservative, the residential energy cost of \$0.06 per kilowatt-hour and an average emission rate of 0.64 kg CO₂/kWh (EIA, 2000) were chosen for the purpose of this analysis. It also should be noted that while the economic analysis of reduction options in these chapters does take LCCP into account, emission forecasts such as those that appear in Exhibit 1.4 do not include indirect emissions.

While the cost analysis focuses on direct and some indirect costs, it does not incorporate indirect societal benefits associated with reducing emissions of greenhouse gases. In particular, it does not attempt to quantify the avoided costs of mitigating potential damages associated with the effects of increased emissions and concentrations of greenhouse gases (for more information on these potential damages, see Pearce *et al.*, 1996). This is consistent with EPA's analysis of options and costs of reducing methane emissions and with the general approach to consider costs and benefits from the standpoint of the decision-makers implementing emission reduction actions.

1.5 Marginal Abatement Curve

The high GWP gas MAC is shown in Exhibits 1.6 and 1.7 at four and eight percent discount rates, respectively. Each of these two curves uses the appropriate schedule of emission reductions and costs for all of the high GWP gases as presented in Exhibits 1.8 and 1.9. The MAC illustrates emission reductions achievable at increasing values of carbon (\$/TCE).

The MAC is derived by rank ordering individual reduction opportunities by cost per emission reduction amount. Any point along a MAC represents the marginal cost of abating an additional amount of high GWP gas. Any emission reduction corresponding to a zero or negative \$/TCE value illustrates a dual price-signal market, where the savings in high GWP gas (i.e., from not having to replace for emitted gas volumes, or from process improvements that lower production costs while also reducing emissions) pay for the emission reduction effort alone.² Positive values represent the price of carbon equivalent that an emitter would have to receive in addition to any other savings in order to make the emission reductions cost-effective.

The high GWP gas MAC in Exhibit 1.6 illustrates three key findings. First, substantial emission reductions, 4.2 million metric tons of carbon equivalent (MMTCE), are likely to be cost-effective in the absence of a carbon value (i.e., at \$0/TCE). Second, achievable reductions at carbon values of \$20/TCE and \$100/TCE are estimated at 28.6 MMTCE and 36.2 MMTCE, respectively. Third, above \$40/TCE, the MAC becomes relatively inelastic, that is, largely non-responsive to increasing carbon values. This result is expected, given that the analysis does not incorporate new technology innovations that might arise with greater carbon values, increased research and development (R&D) expenditures, or other unexpected technology advances. In sum, the analysis suggests that over 5 percent of baseline emissions could be reduced through cost-neutral or possibly even cost-beneficial changes, and that viable options exist to reduce baseline emissions by nearly one half.

² These improvements, in many cases, have not yet been made due to various institutional barriers and informational asymmetries that might prevent their implementation.

1.6 Uncertainties and Limitations

The major uncertainties in the analysis stem from those inherent in data projection as well as from the lack of published information on reduction options and their costs. Specific examples of areas of uncertainty include the following.

- The projected emission estimates are tied to factors such as growth in usage and demand for specific products or gases—difficult items to project for many sectors. This also introduces a degree of uncertainty about the emission estimates.
- There is significant uncertainty in the levels of future energy prices and the indirect effects of potential emission reduction options. Simplifying assumptions regarding future energy prices were made in order to incorporate LCCP into the appropriate sector analyses, most notably the refrigeration, air-conditioning, and foams sectors.
- Several options that were included in the MAC analysis might become more or less efficient in the future as a result of technological breakthroughs and other innovations. It is important to note that some of those options currently not considered viable may become so in the future.
- Some of the emission reduction options discussed involve using chemicals (as substitutes) that can potentially impact human health and/or safety. Although some technically feasible options were omitted for this reason, some options that remain may still prove not to be feasible upon further research because of health and/or safety concerns.

The lack of specific information on reduction opportunities in many sectors can be attributed to several factors, including the following.

- For some applications, minimal research has been performed on how to limit emissions of ODS substitutes, including developing alternatives for them. This is particularly true for foams, aerosols, fire extinguishers, and solvents.
- Data on both emissions and reduction costs may be highly proprietary for many industrial processes. This is especially true of PFC emissions from semiconductor manufacturing and aluminum smelting.
- For many mitigation options, accurate measures of potential emission reductions or costs are not available. These options, although they are qualitatively discussed in the relevant chapters, are not included in the MAC analysis.

Exhibit 1.6: Marginal Abatement Curve for U.S. High GWP Gas Emissions in 2010 (at a 4% discount rate)

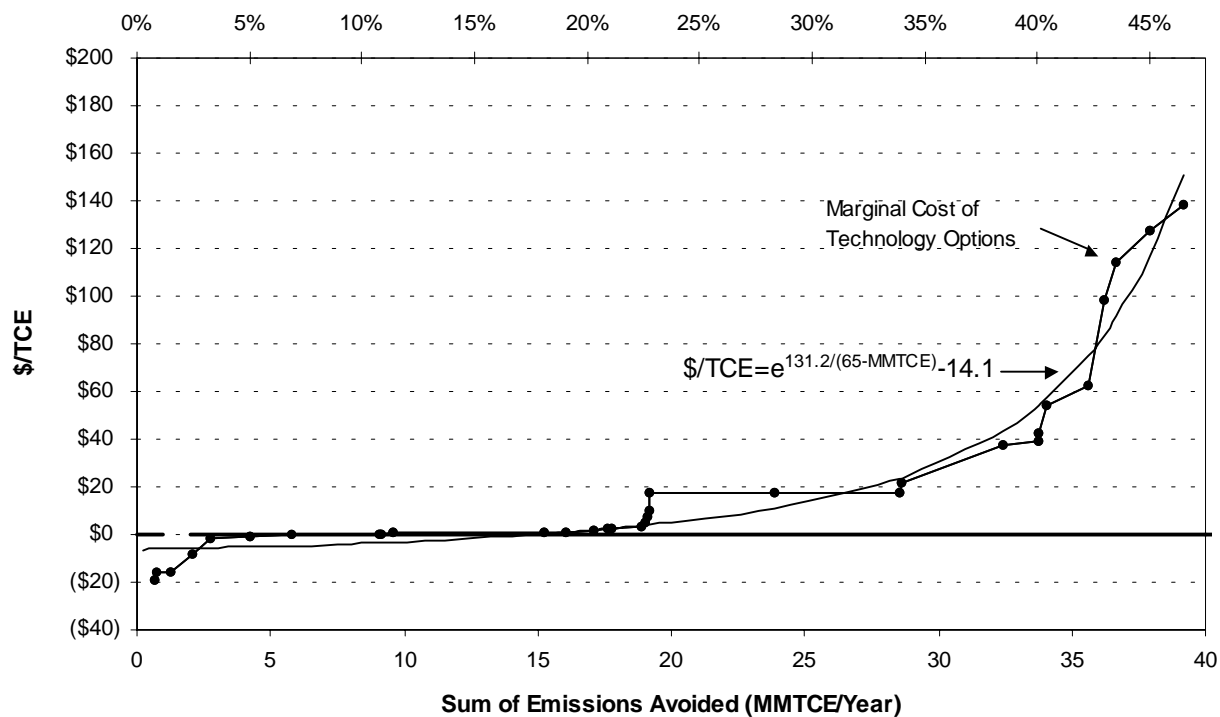


Exhibit 1.7: Marginal Abatement Curve for U.S. High GWP Gas Emissions in 2010 (at an 8% discount rate)

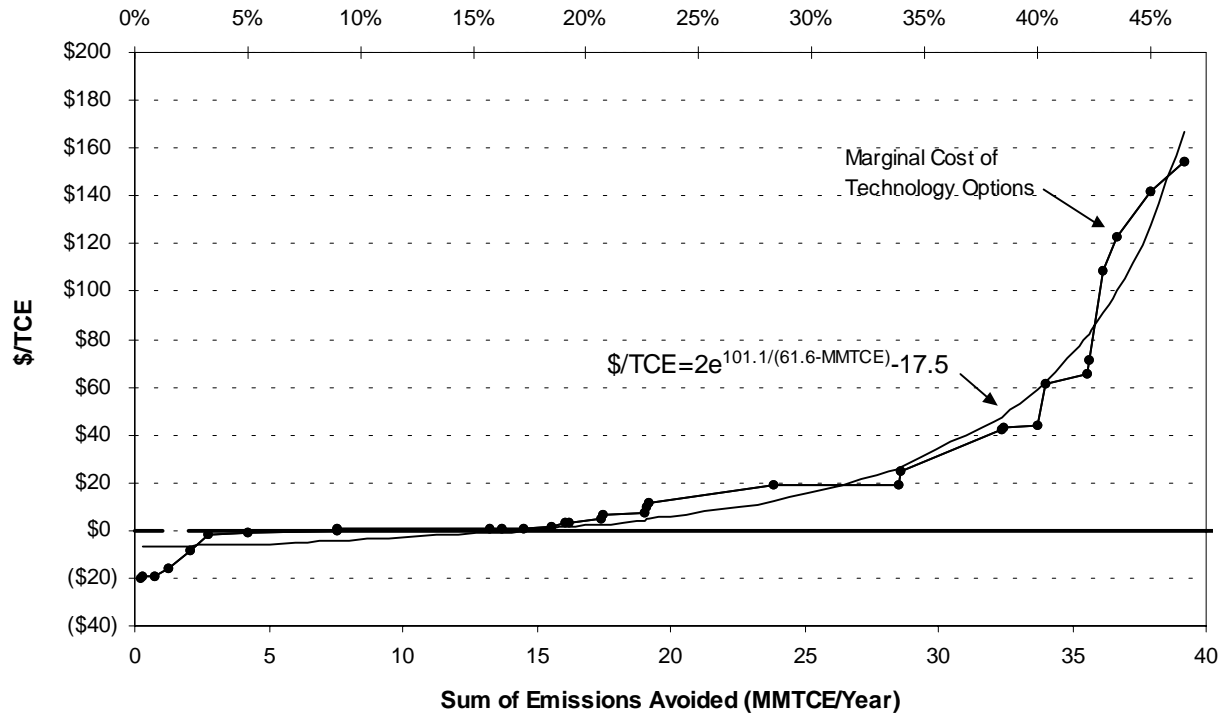


Exhibit 1.8: Composite Marginal Discount Curve Schedule of Options for 2010 (at a 4% discount rate)

#	Source	Activity	Cost (\$/TCE)	Emission Reduction (MMTCE)	Sum of Reduction (MMTCE)	Percent Reduction from 2010 Baseline
1	Aerosols	Hydrocarbon Aerosol Propellants	\$ (20.35)	0.2	0.2	0%
2	Aerosols	Not-in-kind Alternatives	\$ (19.15)	0.5	0.7	1%
3	Fire Extinguishing	Water Mist	\$ (16.19)	<0.05	0.7	1%
4	Foams	PU Spray Foams - Replace HFC-245fa/CO ₂ (water) with hydrocarbons	\$ (15.70)	0.5	1.2	1%
5	Aerosols	Switching to HFC-152a	\$ (8.14)	0.8	2.1	2%
6	Magnesium Smelting	Good Housekeeping	\$ (1.91)	0.7	2.8	3%
7	Magnesium Smelting	SF ₆ Capture/Recycling	\$ (0.90)	1.5	4.2	5%
8	Refrigeration/AC	Replace DX with Distributed System	\$ 0.02	1.5	5.8	7%
9	Magnesium Smelting	SO ₂ Replacement	\$ 0.25	3.3	9.1	11%
10	Aluminum Smelting	Retrofit-Minor: VSS	\$ 0.27	<0.05	9.1	11%
11	Aluminum Smelting	Retrofit-Major: SWPB	\$ 0.43	0.4	9.6	11%
12	HCFC-22 Production	Thermal Oxidation	\$ 0.64	5.7	15.3	18%
13	Solvents	Alternative Solvents	\$ 0.88	0.8	16.1	19%
14	Electric Utilities	Leak Detection and Repair	\$ 1.62	1.0	17.1	20%
15	Electric Utilities	Recycling Equipment	\$ 2.30	0.5	17.6	21%
16	Aluminum Smelting	Retrofit-Major: CWPB	\$ 2.50	0.2	17.8	21%
17	Refrigeration/AC	Leak Reduction Options	\$ 3.58	1.2	18.9	22%
18	Aluminum Smelting	Retrofit-Major: HSS	\$ 5.23	0.1	19.1	23%
19	Aluminum Smelting	Retrofit-Major: VSS	\$ 7.25	0.1	19.1	23%
20	Solvents	NIK Semi-Aqueous	\$ 9.63	<0.05	19.2	23%
21	Foams	PU Appliance Foams - Replace HFC-134a with cyclopentane	\$ 17.18	<0.05	19.2	23%
22	Semiconductor Manufacturing	NF ₃ Drop-In	\$ 17.51	4.7	23.9	28%
23	Semiconductor Manufacturing	NF ₃ Remote Cleaning	\$ 17.51	4.7	28.6	34%
24	Solvents	NIK Aqueous	\$ 21.57	<0.05	28.6	34%
25	Semiconductor Manufacturing	Plasma Abatement	\$ 37.87	3.8	32.4	38%
26	Semiconductor Manufacturing	Capture/Recycling	\$ 39.58	1.3	33.7	40%
27	Solvents	Retrofit Options	\$ 42.45	<0.05	33.8	40%
28	Fire Extinguishing	Inert Gas Systems	\$ 53.86	0.3	34.1	40%
29	Refrigeration/AC	HFC Secondary Loop Systems	\$ 62.57	1.5	35.6	42%
30	Refrigeration/AC	Ammonia Secondary Loop Systems	\$ 98.61	0.6	36.2	43%
31	Foams	PU Spray Foams - Replace HFC-245fa/CO ₂ (water) with CO ₂ (water)	\$ 114.09	0.5	36.7	44%
32	Semiconductor Manufacturing	Catalytic Destruction	\$ 127.29	1.2	37.9	45%
33	Semiconductor Manufacturing	Thermal Destruction	\$ 138.61	1.3	39.2	46%

Exhibit 1.9: Composite Marginal Discount Curve Schedule of Options for 2010 (at an 8% discount rate)

#	Source	Activity	Cost (\$/TCE)	Emission Reduction (MMTCE)	Sum of Reduction (MMTCE)	Percent Reduction from 2010 Baseline
1	Aerosols	Hydrocarbon Aerosol Propellants	\$ (20.32)	0.2	0.2	0%
2	Fire Extinguishing	Water Mist	\$ (19.42)	<0.05	0.3	0%
3	Aerosols	Not-in-kind Alternatives	\$ (19.12)	0.5	0.7	1%
4	Foams	PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with hydrocarbons	\$ (15.64)	0.5	1.2	1%
5	Aerosols	Switching to HFC-152a	\$ (8.09)	0.8	2.1	2%
6	Magnesium Smelting	Good Housekeeping	\$ (1.91)	0.7	2.8	3%
7	Magnesium Smelting	SF ₆ Capture/Recycling	\$ (0.89)	1.5	4.2	5%
8	Magnesium Smelting	SO ₂ Replacement	\$ 0.24	3.3	7.5	9%
9	Aluminum Smelting	Retrofit-Minor: VSS	\$ 0.54	<0.05	7.6	9%
10	HCFC-22 Production	Thermal Oxidation	\$ 0.73	5.7	13.3	16%
11	Aluminum Smelting	Retrofit-Major: SWPB	\$ 0.77	0.4	13.7	16%
12	Solvents	Alternative Solvents	\$ 0.88	0.8	14.5	17%
13	Electric Utilities	Leak Detection and Repair	\$ 1.62	1.0	15.5	18%
14	Electric Utilities	Recycling Equipment	\$ 3.28	0.5	16.1	19%
15	Aluminum Smelting	Retrofit-Major: CWPB	\$ 3.30	0.2	16.2	19%
16	Refrigeration/AC	Leak Reduction Options	\$ 5.08	1.2	17.4	21%
17	Aluminum Smelting	Retrofit-Major: HSS	\$ 6.82	0.1	17.5	21%
18	Refrigeration/AC	Replace DX with Distributed System	\$ 7.21	1.5	19.1	23%
19	Aluminum Smelting	Retrofit-Major: VSS	\$ 9.58	0.1	19.1	23%
20	Solvents	NIK Semi-Aqueous	\$ 11.55	<0.05	19.2	23%
21	Semiconductor Manufacturing	NF ₃ Drop-In	\$ 18.57	4.7	23.9	28%
22	Semiconductor Manufacturing	NF ₃ Remote Cleaning	\$ 18.57	4.7	28.6	34%
23	Solvents	NIK Aqueous	\$ 25.02	<0.05	28.6	34%
24	Semiconductor Manufacturing	Plasma Abatement	\$ 41.95	3.8	32.4	38%
25	Foams	PU Appliance Foams - Replace HFC-134a with cyclopentane	\$ 43.25	<0.05	32.4	38%
26	Semiconductor Manufacturing	Capture/Recycling	\$ 43.99	1.3	33.7	40%
27	Fire Extinguishing	Inert Gas Systems	\$ 61.44	0.3	34.0	40%
28	Refrigeration/AC	HFC Secondary Loop Systems	\$ 65.30	1.5	35.6	42%
29	Solvents	Retrofit Options	\$ 71.24	<0.05	35.6	42%
30	Refrigeration/AC	Ammonia Secondary Loop Systems	\$ 108.67	0.6	36.2	43%
31	Foams	PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with CO ₂ (water)	\$ 122.52	0.5	36.7	44%
32	Semiconductor Manufacturing	Catalytic Destruction	\$ 141.93	1.2	37.9	45%
33	Semiconductor Manufacturing	Thermal Destruction	\$ 154.54	1.3	39.2	46%

1.7 References

- DOS. 1997. *Climate Action Report: 1997*. Submission of the United States of America under the United Nations Framework Convention of Climate Change. Bureau of Oceans and International Environmental Scientific Affairs, Office of Global Climate Change, U.S. Department of State, Washington, D.C., DOS10496. (Available on the Internet at http://www.state.gov/www/global/oes/97climate_report/index.html).
- EIA. 2000. *Annual Energy Outlook 2000*. Energy Information Administration, Washington, DC.
- EPA. 1999. *U.S. Methane Emissions 1990–2020: Inventories, Projections, and Opportunities for Reductions*. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC; EPA 430-R-99-013. (Available on the Internet at <http://www.epa.gov/ghginfo>).
- EPA. 2000. *Inventory of Greenhouse Gas Emissions and Sinks 1990-1998*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC; EPA 236-R-00-001. (Available on the Internet at <http://www.epa.gov/globalwarming/emissions/national/download.htm>).
- EPA. 2001. *Inventory of Greenhouse Gas Emissions and Sinks 1990-1999*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC; EPA 236-R-01-001. (Available on the Internet at <http://www.epa.gov/globalwarming/emissions/national/download.htm>).
- Hayhoe, K., A. Jain, H. Pitcher, C. MacCracken, M. Gibbs, D. Wuebbles, R. Harvey, D. Kruger. 1999. *Costs of Multi-greenhouse Gas Reduction Targets for the USA*. *Science* (Oct 29, 1999), pp. 905-906.
- OMB. 2000. *Guidelines to Standardize Measures of Costs and Benefits and the Format of Accounting Statements*. Memorandum for the Heads of Departments and Agencies from Jacob Lew, OMB Director (March 22, 2000).
- Pearce, D.W., W.R. Cline, A.N. Achantas, S. Fankhauser, R.K. Pachavri, R.S.J. Tol, P. Vellinga. 1996. *The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control*, in J. Bruce, H. Lee, and E. Haites (eds.), *Climate Change 1995: Economic and Social Dimensions of Climate Change: Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. World Meteorological Organization and United Nations Environment Programme 1996.
- Reilly, J., R. Prin, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov, C. Weng. 1999a. *Multi-gas Assessment of the Kyoto Protocol*. *Nature* (October 7, 1999), pp. 549-555.
- Reilly, J., R.G. Prinn, J. Harnisch, J. Fitzmaurice, H.D. Jacoby, D. Kicklighter, P.H. Stone, A.P. Sokolov, and C. Wang. 1999b. *Multi-gas Assessment of the Kyoto Protocol*. Report No. 45, MIT Joint Program on the Science and Policy of Global Change, Boston, MA, January 1999. (Available on the Internet at <http://web.mit.edu/globalchange/www/rpt45.html>).
- Schimel, D., D. Alves, I. Enting, M. Heimann, F. Joos, D. Raynaud, T. Wigley, M. Prather, R. Derwent, D. Ehhalt, P. Fraser, E. Sanhueza, X. Zhou, P. Jonas, R. Charlson, H. Rodhe, S. Sadasivan, K.P. Shine, Y. Fouquart, V. Ramaswamy, S. Solomon, J. Srinivasan, D. Albritton, R. Derwent, I. Isaksen, M. Cal, D. Wuebbles. 1995. *Radiative Forcing of Climate Change*, in J.T. Houghton, L.G. Meirafilho, B.A. Callander, N. Harris, A. Kettenberg (eds.), *Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. World Meteorological Organization and United Nations Environment Programme, 1995.

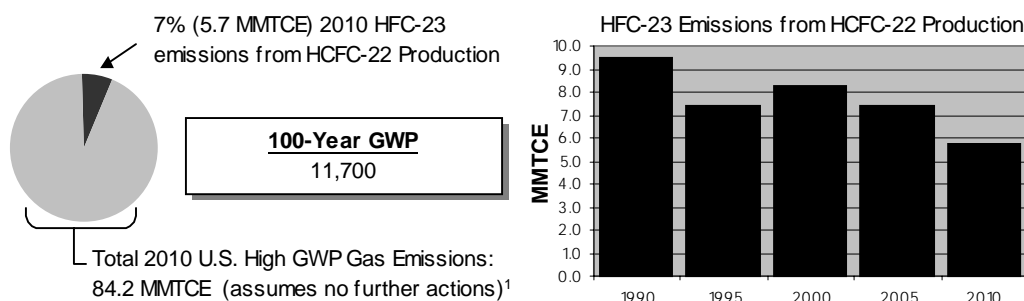
2. Cost and Emission Reduction Analysis of HFC-23 Emissions from HCFC-22 Production in the United States

2.1 Introduction

Trifluoromethane (HFC-23 or CHF_3) has a 100-year global warming potential (GWP) that is 11,700 times greater than the warming potential of carbon dioxide over the same period. HFC-23 is generated as a byproduct during the production of chlorodifluoromethane (HCFC-22), currently used in refrigeration and air-conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Under a business-as-usual scenario (i.e., no actions), by 2010, HCFC-22 production in the United States would be expected to emit approximately 5.7 million metric tons carbon equivalent (MMTCE) of HFC-23 (see Exhibit 2.1).¹ However, actual emissions are expected to be lower, in part as a result of emission mitigation actions by industry that are not included in the business-as-usual baseline. Current and potential applications for HCFC-22 include:

- **Aerosol propellants**, as alternatives to CFC-12 in a few permitted uses;
- **Foam blowing**, as an alternative to CFC-12 in polyurethane foams and in polystyrene extruded boardstock and billet;
- **Refrigeration**, as an alternative to R-502 (a blend of CFC-115 and HCFC-22) in most cooling systems, air-conditioning systems, heat pumps, and in blends to replace other CFCs in various cooling systems (Heijnes *et al.*, 1998); and
- **Tetrafluoroethylene manufacture**, as a feedstock used in the process of tetrafluoroethylene production.

Exhibit 2.1: U.S. Historical and Baseline HFC-23 Emissions from HCFC-22 Production



¹ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

Under the Clean Air Act, manufacture and import of HCFC-22, except for use as a feedstock and in equipment manufactured before 2010, are scheduled to be phased out by January 1, 2010. All manufacture and import except for chemical feedstocks is scheduled to be phased out by January 1, 2020. Four U.S. companies account for approximately 39 percent of all global and 100 percent of U.S. HCFC-22 production: Allied Signal, Inc.; DuPont; MDA Manufacturing; and ATOFINA-North America (Rand *et al.*, 1999).

Manufacturers of HCFC-22 in the United States are voluntarily working to reduce emissions of HFC-23 that are generated as a byproduct of HCFC-22 manufacture (Exhibit 2.1). Under this program, U.S. manufacturers have pledged to reduce HFC-23 emissions from HCFC-22 manufacturing by 4.1 MMTCE by 2000 through the use of cost-effective mitigation measures (DOS, 1999; Bernhardt, 2000).

2.2 Historical and Baseline HFC-23 Emission Estimates

Historical emissions of HFC-23 from HCFC-22 production are shown in Exhibit 2.2, and include emission reductions seen under the HCFC-22 CCAP Program. To estimate future baseline emissions (for the years 2000, 2005, and 2010), EPA assumes that future average HFC-23 emission factors will remain constant at an average of 1995-97 levels and HCFC-22 production will initially increase and then decline as non-feedstock HCFC production is phased out. Future baseline emission estimates do not include CCAP program reductions (see Exhibit 2.3).

Exhibit 2.2: Historical U.S. HFC-23 Emissions from HCFC-22 Production (1990-1999)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	9.5	8.4	9.5	8.7	8.6	7.4	8.5	8.2	10.9	8.3
Emissions (metric tons HFC-23)	2,974	2,632	2,974	2,726	2,692	2,316	2,667	2,573	3,419	2,598

Source: EPA, 2001.

Note: Conversion to MMTCE is based on a GWP of 11,700.

Exhibit 2.3: Baseline U.S. HFC-23 Emissions from HCFC-22 Production (2000-2010)

	2000	2005	2010
Emissions (MMTCE)	8.2	7.4	5.7
Emissions (metric tons HFC-23)	2,583	2,313	1,790

Notes:

Forecast emissions are based on a business-as-usual scenario, assuming no further action.

Conversion to MMTCE is based on a GWP of 11,700.

2.3 HFC-23 Emission Reduction Opportunities

Historically, a majority of HFC-23 emissions were vented to the atmosphere. However, two options have been identified as technically viable measures to reduce HFC-23 emissions from HCFC-22 production: (1) manufacturing process optimization, and (2) the destruction of HFC-23 by thermal oxidation (March Consulting Group, 1998; March Consulting Group, 1999).

Process Optimization

Process optimization and modifying production equipment can both optimize HCFC-22 production and reduce HFC-23 emissions. Process optimization is relatively inexpensive and is likely to be most effective in reducing the emissions from plants that are generating HFC-23 at a rate of three to four percent. All plants in the United

States have already implemented some optimization resulting in reductions of HFC-23 emissions. These plants may achieve further reductions through further process optimizations, but these reductions are likely to be more modest (Rand *et al.*, 1999).

Thermal Oxidation

Thermal oxidation (the process of oxidizing HFC-23 to CO₂, hydrogen fluoride (HF), and water) is a demonstrated technology for the destruction of halogenated organic compounds. For example, destruction of more than 99 percent of HFC-23 can be achieved under optimal conditions (i.e., a relatively concentrated HFC-23 vent stream with a low flow rate) (Rand *et al.*, 1999). In practice, units will experience some downtime based on the extreme corrosivity and high temperatures required for complete destruction. Although typical incinerators that burn only HFC-23 produce six pounds of CO₂ for every one pound of HFC-23 burned, almost all of the CO₂ produced is prevented from entering the atmosphere by scrubbers in the smoke stack. This reduction in CO₂ emissions occurs while scrubbing to remove HF from the waste stream (Oldach, 2000).

2.4 Cost Analysis

Thermal oxidation is an effective mitigation measure to reduce HFC-23 emissions. It has been estimated that the total installed capital costs for a thermal oxidation system are approximately \$7 million per plant with total annual operational costs of \$200,000 per year (Honeywell, 2000). Some U.S. plants have already started to use this technology; the installation of such systems for other plants is technologically feasible. Cost estimates for such systems are based upon the best available industry assessments and actual costs of some systems could differ from these estimates.

Exhibit 2.4 presents a summary of HFC-23 emission reductions from thermal oxidation at both four and eight percent discount rates by cost per metric ton of carbon equivalent (TCE). At the four percent discount rate, thermal oxidation measures could be implemented at an estimated \$0.64 per TCE, thereby eliminating nearly all baseline emissions at a relatively low cost.

Exhibit 2.4: Emission Reductions and Cost in 2010						
Option	Break-even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate					
	4%	8%	MMTCE	Percent	MMTCE	Percent
Thermal Oxidation	0.64	0.73	5.7	99.9%	5.7	99.9%
Notes:						
2010 Baseline emissions from this sector equal 5.7 MMTCE.						
Conversion to MMTCE is based on a GWP of 11,700.						
Sums might not add to total due to rounding.						

2.5 References

Bernhardt, Steven. 2000. Personal Communication. Re: letter of intent from Kevin Fay, Executive Director of the Alliance For Responsible Atmospheric Policy to EPA Administrator Carol Browner, October 18, 1993.

DOS (U.S. Department of State). 1999. U.S. Submission on Ways and Means of Limiting Emissions of Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulfur hexafluoride (SF₆). Submitted to the UN Framework Convention on Climate Change. (Available on the Internet at http://www.state.gov/www/global/global_issues/climate/990716_unfccc1_subm.html).

EPA. 2001. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC. (Available on the Internet at <http://www.epa.gov/globalwarming/emissions/national/download.html>).

Heijnes, H., M. Van Brummelen, and K. Blok. 1998. *Reduction of Emissions of HFCs, PFCs, and SF₆ in the European Union*. Commissioned by the European Community, DGXI. M717. ECOFYS. P.O. Box 8408, NL-3505 RK Utrecht, Netherlands.

Honeywell, Gail E. Lehman. 2000. Letter, Re: Estimates of U.S. Emissions of High Global Warming Potential Gases and the Costs of Reductions, Review Draft, March 2000, sent July 26, 2000.

March Consulting Group. 1998. *Opportunities to Minimize Emissions of Hydrofluorocarbons (HFCs) from the European Union*. Final Report. Prepared by March Consulting Group, United Kingdom, for the European Commission.

March Consulting Group. 1999. *UK Emissions of HFCs, PFCs, and SF₆ and Potential Emission Reduction Options*. Final Report. Prepared by March Consulting Group, United Kingdom.

Oldach, Robert. Senior Engineer with DuPont's Research Group. 2000. Phone conversation with Carrie Smith on August 10, 2000.

Rand, S., D. Ottinger, and M. Branscome. 1999. *Opportunities for the Reduction of HFC-23 Emissions from the Production of HCFC-22*. IPCC/TEAP Joint Expert Meeting. Petten, Netherlands. May 26-28, 1999.

3. Cost and Emission Reduction Analysis of SF₆ Emissions from Electric Power Transmission and Distribution Systems in the United States

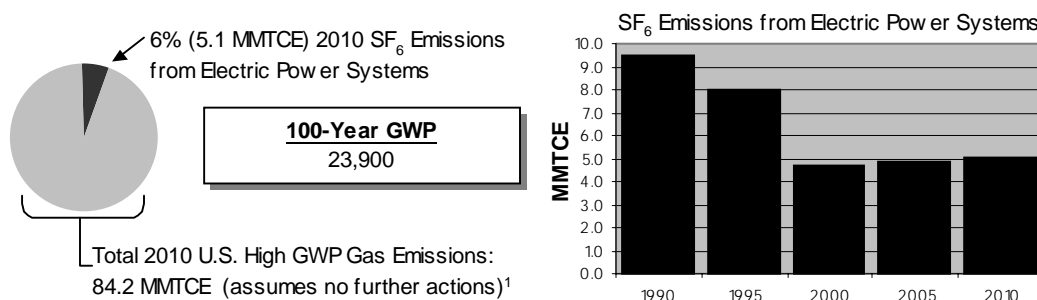
3.1 Introduction

Sulfur hexafluoride (SF₆) is a colorless, odorless, non-toxic, and non-flammable gas used as an insulator in electric transmission and distribution equipment. SF₆ has a 100-year GWP that is 23,900 times that of carbon dioxide and has an atmospheric lifetime of 3,200 years (EPA, 2000). By 2010, under a business-as-usual scenario, the United States would be expected to emit 5.1 MMTCE of SF₆ (see Exhibit 3.1).¹ However, as noted below, actual emissions in the future are expected to be lower as a result of voluntary industry actions.

SF₆ is a manufactured gas primarily used as an electrical insulator in equipment that transmits and distributes electricity. Leaks from this equipment and venting of the gas during equipment servicing and disposal of equipment are the main sources of emissions. Worldwide, an estimated 80 percent of SF₆ use is in electrical transmission and distribution systems. The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. SF₆ replaced flammable insulating oils in many electricity transmission applications and allows for the employment of more compact electrical equipment in dense urban areas.

Gas-insulated circuit breakers are the largest source of fugitive SF₆ emissions in U.S. electricity systems. In addition, there are somewhat less than 100 gas-insulated substations (GIS) that constitute a smaller source of SF₆ emissions. In general, older equipment produces more fugitive emissions than newer equipment. SF₆ can also be released when equipment is opened for routine servicing. For example, the

Exhibit 3.1: SF₆ Emissions from Electric Power Transmission and Distribution Systems



¹ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

older dual-pressure breakers, which need servicing every six years or so, are a strong source of fugitive emissions. The newer equipment is rarely opened for routine servicing because the internal components last a longer time (10-12 years). Sometimes, SF₆ is vented to the atmosphere during servicing, but increased environmental awareness and large increases in the cost of SF₆ during the mid-1990's have significantly reduced this practice.

The SF₆ Emission Reduction Partnership for Electric Power Systems began in early 1999. This partnership is one of the newest voluntary initiatives sponsored by EPA under the CCAP. The Partnership is a collaborative effort between EPA and the electric power industry to identify technically and economically feasible actions that reduce SF₆ emissions. Industry partners submitted their first annual reports in mid-2000.

3.2 SF₆ Baseline Emission Estimates

Exhibit 3.2 presents estimated historical SF₆ emissions from U.S. electric power systems. Emission estimates are based on annual reports for 1999 received via the SF₆ Emission Reduction Partnership for Electric Power Systems. Although the partner utilities only represent a subset of the U.S. utility population, regression analysis demonstrates that a statistically significant relationship exists between reported emissions and the size of their respective transmission systems (measured in miles). This relationship was used to calculate emissions on the national level for 1999. Since partner reports were not available for other years, the 1990 through 1998 historical emissions were scaled according to world sales of SF₆ to utilities (Smythe, 2000). Emissions were forecasted for 2000 to 2010 by assuming that SF₆ use would grow at a rate of 0.7 percent per year, based upon growth in electricity consumption and a smaller but offsetting decline in average equipment charge size.

Exhibit 3.3 presents future baseline emission estimates. Future emission estimates do not include reductions that might occur under CCAP.

Exhibit 3.2: Historical SF₆ Emissions from Electric Power Systems (1990-1999)										
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	9.5	9.9	9.2	10.4	9.5	8.0	8.1	7.4	6.1	4.7
Emissions (metric tons SF₆)	1,455	1,513	1,405	1,588	1,464	1,234	1,247	1,141	939	723

Source: EPA estimates.
Note: Conversion to MMTCE is based on a GWP of 23,900.

Exhibit 3.3: Baseline SF₆ Emissions from Electric Power Systems (2000-2010)			
	2000	2005	2010
Emissions (MMTCE)	4.7	4.9	5.1
Emissions (metric tons SF₆)	723	748	775

Notes:
Forecast emissions are based on a business-as-usual scenario, assuming no further action.
Conversion to MMTCE is based on a GWP of 23,900.

3.3 SF₆ Emission Reduction Opportunities

The most promising options to reduce SF₆ emissions can be grouped into four categories: recycling, leak detection and repair, equipment replacement, and use of advanced leak detection technologies. Each is summarized below.

Use of Recycling Equipment

Recycling equipment allows SF₆ to be captured and recycled rather than vented to the atmosphere during equipment maintenance and retirement. EPA conservatively estimates that SF₆ recycling can eliminate 10 percent of total SF₆ emissions from U.S. electric power systems.

Leak Detection and Repair

Many U.S. utilities already implement cost-effective leak detection and repair. Normal procedures require taking units out of service to search for SF₆ leaks. If thoroughly implemented in the United States, EPA estimates that leak detection and repair could reduce SF₆ emissions from this sector by about 20 percent.

Equipment Replacement/Accelerated Capital Turnover

The owners and operators of electric utilities often keep old systems in operation because the systems tend to be reliable. However, reliability can be improved cost-effectively by replacing equipment to reduce greenhouse gas emissions, as experienced in the natural gas and refrigeration industries. Since much of the SF₆ emitted from electric power transmission and distribution systems comes from older equipment, which tends to use larger amounts of SF₆ and have higher leak rates than newer equipment, replacing the older capital stock would reduce SF₆ emissions and improve overall efficiency. Perhaps 50 percent or more of all emissions from older equipment could be avoided if all older equipment were replaced. However, the uncertainty created by the rapidly evolving electricity market has made utilities reluctant to invest in the replacement of older breakers with new, “tighter” units (Bolin, 1998).

Advanced Leak Detection Technologies

A laser leak detection system is capable of finding leaks with a high degree of accuracy without any modifications or physical connections to circuit breakers. The advantages over traditional leak detection procedures are the ability to perform leak detection without having to take equipment out of service and the dramatic reduction in time necessary to detect a leak. The GasVue laser camera, a laser leak detection system developed with the support of the Electric Power Research Institute (EPRI) by Laser Imaging Systems of Punta Gorda, Florida, has been successfully used at a wide range of utilities in the United States and abroad (Moore, 1999).

3.4 Cost Analysis

The most promising options to reduce SF₆ emissions from electric power systems are SF₆ recycling and SF₆ leak detection and repair. SF₆ recycling could reduce emissions by about 10 percent and is currently cost-effective. Leak detection and repair could reduce emissions cost-effectively by 20 percent. All cost analyses were based on a four percent discount rate (Exhibit 3.4), a ten-year project lifetime, and an SF₆ price of \$8.00 per pound. For sensitivity comparisons the cost analysis is also provided at an eight percent discount rate. The financial assumptions and results specific to each emission reduction option are presented below.

Recycling Equipment

The capital costs of recycling equipment range from around \$5,000 to over \$100,000 per utility. For this analysis, typical recycling expenditures have been set at \$25,500 per utility. However, this capital investment produces O & M savings of nearly \$1,600 per year per utility due to reduced purchases of SF₆. In 2010 this option could reduce emissions by 0.5 MMTCE or ten percent of baseline emissions at a savings of \$2.30 per metric ton of carbon equivalent (TCE).

Leak Detection and Repair

There are no capital costs associated with leak detection and repair and O&M costs are estimated to be \$2,190 per utility due to the increased labor costs associated with this option. This option could reduce emissions by 1.0 MMTCE in 2010, 20 percent of baseline emissions, at a cost of \$1.62 per TCE.

Equipment Replacement/Accelerated Capital Turnover

The capital costs of this option vary by equipment type. Circuit breakers (below 34.5 kV) may be replaced with vacuum breakers. The replacement cost varies from \$25,000 to \$75,000 per unit. Medium and high voltage breakers are expected to continue to use SF₆ because no other option is currently available. Older breakers are assumed to leak more and are being replaced by new equipment (as part of routine turnover) at a cost of approximately \$200,000 to \$750,000 per unit. Additional research into the existing equipment stock and potential for replacement will be necessary to develop cost estimates for emission reductions.

Advanced Leak Detection Technologies

The capital cost per GasVue leak detection camera is approximately \$100,000. Additional research into the potential emission reductions from this option will be necessary to develop estimates for O&M costs and the total cost of emission reductions.

Exhibit 3.4: Emission Reductions and Cost 2010 (at 4% and 8% discount rate)

Option	Break-even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate					
	4%	8%	MMTCE	Percent	MMTCE	Percent
Leak Detection	1.62	1.62	1.0	20%	1.0	20%
Recycling Equipment	2.30	3.28	0.5	10%	1.5	30%

Notes:

Values in parenthesis indicate savings.

2010 baseline SF₆ emissions from electric utilities equal 775 metric tons SF₆ or 5.1 MMTCE.

This table is based on the GWPs listed in the Introduction to the report.

3.5 References

Bolin, P.C. 1998. IEEE Power Engineering Society, Subcommittee.

Moore, T. 1999. *Seeing SF₆ in a New Light*. EPRI Journal. Summer 1999. Palo Alto, California.

Smythe, Katie D. 2000. "Production and Distribution of SF₆ by End-Use Application." Presented at the *Conference on SF₆ and the Environment: Emission Reduction Strategies*, November 2-3, 2000, San Diego, California. (Available online at <http://www.epa.gov/highgwpl/sf6/pdf/smythep.pdf>).

4. Cost and Emission Reduction Analysis of SF₆ Emissions from Magnesium Production and Parts Casting in the United States

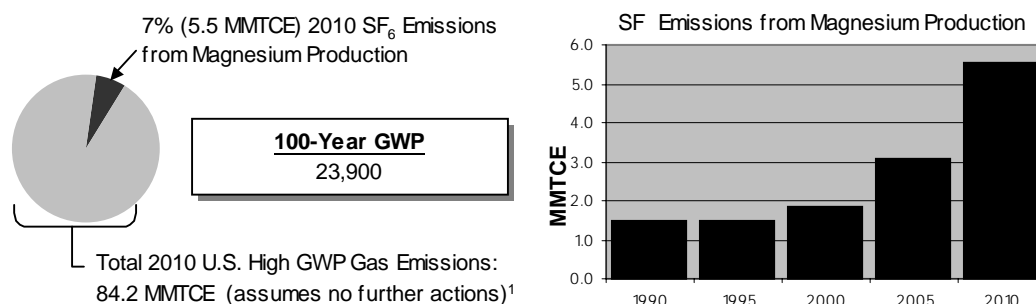
4.1 Introduction

The magnesium metal production and casting industry uses sulfur hexafluoride (SF₆) as a cover gas to prevent the violent oxidation of molten magnesium in the presence of air. SF₆ is a colorless, odorless, non-toxic, and non-flammable gas with a GWP that is 23,900 times that of carbon dioxide over a 100-year time horizon and an atmospheric lifetime of 3,200 years (EPA, 2000). Under a business-as-usual scenario, by 2010 the United States could emit 5.5 million metric tons of carbon equivalent (MMTCE) SF₆ from magnesium production and processing (see Exhibit 4.1).¹ However, as noted below, actual emissions are expected to be lower as a result of voluntary industry actions.

Small concentrations of SF₆ in combination with carbon dioxide and/or dry air are blown over molten magnesium metal to induce the formation of a protective crust. The industry adopted the use of SF₆ to replace sulfur dioxide (SO₂), which is toxic and requires careful handling, to protect worker safety. The SF₆ technique is used by both producers of primary magnesium metal and by most magnesium part casters. Historically, more than half of SF₆ emissions from the U.S. magnesium industry have come from primary magnesium production. However, because of production facility closures and continued growth in the magnesium casting sector, primary production emissions currently account for less than 50 percent. The magnesium recycling industry, for the most part, continues to employ sulfur dioxide as a covergas.

In 1999, EPA began the voluntary SF₆ Emission Reduction Partnership for the Magnesium Industry. Individual magnesium producer or casting company partners signed a memorandum of understanding (MOU) with EPA committing to report their emissions of SF₆ annually and to take cost-effective actions to reduce those emissions. EPA works together with its industry partners to review and evaluate

Exhibit 4.1: U.S. Historical and Baseline SF₆ Emissions from Magnesium Production



¹ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

emission reduction strategies and technologies, promote technical information sharing by preparing annual reports and hosting technical conferences, record and verify the partners' progress, and provide positive public recognition for the partners' achievements.

4.2 Historical and Baseline SF₆ Emission Estimates

Exhibit 4.2 presents historical SF₆ emissions from magnesium production and processing (EPA, 2001).

Exhibit 4.2: Historical SF₆ Emissions from the Magnesium Industry (1990-1999)										
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	1.5	1.5	1.5	1.5	1.4	1.5	1.5	2.0	1.7	1.7
Emissions (metric tons)	230	230	230	226	213	230	234	314	264	255

Source: EPA, 2001.
Note: Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

Baseline emission estimates for 2000, 2005, and 2010 are presented in Exhibit 4.3. These estimates do not include reductions anticipated under the SF₆ Emission Reduction Partnership for the Magnesium Industry.

Exhibit 4.3: Baseline SF₆ Emissions from the Magnesium Industry (2000-2010)			
Year	2000	2005	2010
Emissions (MMTCE)	1.8	3.1	5.5
Emissions (metric tons)	283	474	850

Note:
Forecast emissions are based on a business-as-usual scenario, assuming no further action.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

4.3 SF₆ Emission Reduction Opportunities

The most promising options to reduce SF₆ emissions from magnesium production and processing can be grouped into the six categories listed below.

Good Housekeeping

The measures referred to as “good housekeeping” result in more efficient use of SF₆ in magnesium production and processing and are currently implemented at some facilities. Examples of good housekeeping include:

- Daily SF₆ leak detection and maintenance, including:
 - Checks of the crucible's lid tightness, SF₆ flow meter, and flow meter settings.
 - Inspection and record keeping of SF₆ line leaks and flow rates.

- Monthly SF₆ leak detection and maintenance, including:
 - Extensive maintenance checks for SF₆ leakage.
 - SF₆ flow meter calibration.
- Installation of centralized covergas mixers and semi-annual calibration of existing covergas mixers (following guidelines for SF₆/CO₂/air mixtures to minimize SF₆ concentrations).
- Actions to minimize SF₆ gas buoyancy (minimize temperature of furnace, use external manifolds to supply gas at coolest possible temperature, feed gas at high velocity).
- Assuring cover gas quality (e.g., minimizing moisture if ambient air is used).

If good housekeeping measures were thoroughly implemented throughout the U.S. magnesium industry, EPA estimates that emission reductions could be on the order of 30 percent. This reduction potential is based on expert opinion and the effectiveness of directed inspection and maintenance in similar emission reduction programs, such as those reported by industry partners in the Natural Gas STAR Program, an EPA-industry partnership that promotes cost-effective reductions in methane emissions.

Process Optimization

The practices referred to as “process optimization” also result in the more efficient use of SF₆ in magnesium production and processing. These measures are incremental to “good housekeeping” and represent the latest developments in technology and management practices. Some process optimization measures have not yet been implemented at any facility. There are currently no emission reduction or cost data available for these measures. Examples of process optimization include:

- Installation of cooling pipes along magnesium ingot casting machines (applicable to metal production only). Cooling pipes reduce the amount of time that magnesium is in a molten state, and therefore reduce the amount of time during which a covergas like SF₆ is needed;
- Upgrade of magnesium ingot loading doors in re-melt furnaces at processing facilities to minimize fugitive emissions of SF₆ (e.g., doors with air lock systems);
- Installation of switches to increase (decrease) flow rate when the loading door opens (closes) rather than a constant high flow rate system; and
- Reconfiguration of cover gas distribution system outlets to optimize SF₆ use.

Capture/Recycle SF₆

Air Liquide developed an SF₆ capture/recycle system that could reduce SF₆ emissions by up to 95 percent from current levels (Li, 2000). This patented process uses semi-permeable hollow membrane fibers to separate SF₆ from CO₂ and air in the spent cover gas. The captured SF₆ can be re-used by the industry on-site. The recovery cost—ranging from \$3.60 to \$8.00 per pound of captured SF₆—would be cheaper than current market prices for virgin SF₆. Air Liquide plans to market the system on a service contract basis covering installation, start-up, and maintenance for a monthly fee.

Replace SF₆ with SO₂

SF₆ was introduced to replace SO₂, as the latter is toxic and has a low threshold (2 PPM) for workplace exposure. SO₂ usage also corrodes casting equipment. However, safer SO₂ handling procedures and the relatively low cost of SO₂ as compared to SF₆ makes SO₂ more attractive. SO₂ replacement could potentially eliminate a large portion of SF₆ emissions from the magnesium industry, but there are substantial costs associated with switching to SO₂ in terms of increased capital cost for metering and distribution, gas scrubbing, and corrosion protection in surrounding structures. SO₂ is subject to other forms of air and safety regulation and it is also a major cause of acid precipitation.

Replace SF₆ with HFC-134a

Preliminary laboratory trials by CSIRO, Australia have shown that the gas 1,1,1,2-tetrafluoroethane (C₂H₂F₄) or HFC-134a (largely used as a refrigerant gas to replace the CFC refrigerant R-12) provides excellent protection of molten magnesium. At one-third the cost of SF₆, HFC-134a has no ozone depleting potential (ODP) and a GWP of 1,300, which is substantially lower than the 23,900 GWP for SF₆.

The disadvantage with HFC-134a is that the elevated temperature of the magnesium melt will cause some decomposition of HFC-134a into HF gas and other components. HF gas may affect operator safety and accelerate corrosion of equipment (Cashion *et al.*, 2000). Nevertheless, substituting HFC-134a for SF₆ is a promising alternative.

The Magshield[®] System

The Magshield[®] system was developed by HATCH and tested at Lunt Manufacturing Company. The system produces BF₃, a protective gas liberated through the decomposition of a solid fluoroborate in a furnace. Gas is thus generated only when required. BF₃ is not a greenhouse gas and prospects of a major spill of the fluoroborate are virtually non-existent as the fluoroborate exists in solid form. BF₃-generating costs are significantly lower than SF₆ and BF₃ is easier to scrub with water. The amount of waste sludge generated may also be less than SF₆ (Revankar *et al.*, 2000).

Thixomolding[®] (applicable to casting only)

Thixomolding[®] is a process invented and sold by Thixomat for the high speed molding for metal parts that does not involve molten magnesium and therefore eliminates the need of a covergas like SF₆. During Thixomolding[®], high-speed mixing heats magnesium metal granules into a semi-solid phase. This semi-solid material is then injected into a mold. Thixomolding[®] is marketed primarily to companies that manufacture plastic molding and it is mostly popular with manufacturers of small consumer electronics in Asia. As Thixomat is not focusing on marketing Thixomolding[®] as an alternative to conventional magnesium casting, Thixomolding[®] is not expected to diminish conventional diecasting or SF₆ use in the United States in the foreseeable future (Lebean, 1999).

4.4 Cost Analysis

This analysis considers SF₆ emission reductions for four incremental possibilities that collectively could reduce emissions by 99 percent. The reduction possibilities summarized below include SO₂ replacement, good housekeeping, and Air Liquide's capture/recycle technology. HFC-134a replacement was not included in the cost as research on HFC-134a for this purpose is still in its early stages. Further research on optimum concentrations and flow rates for industrial usage of HFC-134a is needed in order to identify costs (Cashion *et al.*, 2000). Given current market conditions, there are also no plans to market Magshield® on an industry-wide level (Schultz, 2001).

Exhibit 4.4 summarizes the potential emission reductions and associated costs of SF₆ reduction per TCE.

Replace SF₆ with SO₂

Capital costs for replacing SF₆ with SO₂ in 2000 are estimated to be \$15.887 million. This includes retrofitting expenses as well as the purchase of SO₂-compatible equipment (CHEMinfo, 1998). A one-time \$310,927 start-up cost for a worker safety training program for all firms is also included in the capital costs. For this analysis, EPA assumed that 60 percent of SF₆ emissions could be reduced by SO₂ replacement in 2010 at a cost of \$0.25 or \$0.24 per TCE depending on the discount rate applied.

Good Housekeeping

Good housekeeping results in more efficient SF₆ use. There are no capital costs associated with good housekeeping. Annual O&M savings estimates for the whole industry are based upon estimated leakage rates. Firms not implementing the SO₂ replacement technology could opt for good housekeeping and this could reduce SF₆ emissions by a further 0.7 MMTCE or 12 percent of 2010 baseline emissions at savings of \$1.91 per TCE.

Capture/Recycle SF₆

Since this technology is offered on a service contract basis, investment is therefore limited to the cost of collecting and conducting the spent gas to the preferred system location in the plant. This is a minimal one-time cost borne by the client. A capital cost of \$100,000 was assumed for the cost analysis. The size of the system, and thus its associated monthly fee, will vary depending upon volume of treated gas, concentration of SF₆ in the exhaust line, and target concentration of SF₆ required for re-injection as feed gas. The cost per pound of recovered SF₆ (including electric power used to operate the system) was estimated at \$7 (Li, 2000). In view of the modular nature of the system, the cost per pound of recovered SF₆ will probably vary little with total treated volume. Similarly, for the same treated volume and initial concentration, a higher required final concentration results in a marginally higher unit recovery cost. However, for the same target conditions, a lower initial concentration can increase unit recovery cost significantly. In the worst case, the cost per pound of SF₆ recovered should still be cheaper than the current price of purchased gas and therefore, O&M savings were conservatively assumed to be identical to good housekeeping. The cost analysis shows that the capture and recycling of SF₆ could reduce 1.5 MMTCE or 27 percent of baseline emissions at savings of \$0.90 or \$0.89 per TCE, depending on the discount rate.

Exhibit 4.4: Emission Reductions and Cost in 2010

Option	Break-even Cost (\$/TCE) Discount Rate		Incremental Reductions		Sum of Reductions	
	4%	8%	MMTCE	Percent	MMTCE	Percent
Good Housekeeping	(1.91)	(1.91)	0.7	12%	0.7	12%
SF ₆ Capture/Recycle	(0.90)	(0.89)	1.5	27%	2.2	39%
SO ₂ Replacement	0.25	0.24	3.3	60%	5.5	99%

Notes:

2010 baseline SF₆ emissions from the magnesium industry equal 5.5 MMTCE.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

Values in parenthesis indicate savings.

Sums might not add to total due to rounding.

4.5 References

Cashion, S.P., Ricketts, N.J., Forst, M.T. and Korn, C. CRC for Cast Metals Manufacturing (CAST). *The Protection of Molten Magnesium and its Alloys during Diecasting*. Paper delivered to 8th Annual IMA Seminar on Magnesium in Automotive Application, Aalen, Germany, 12-19 June 2000.

CHEMinfo. 1998. *Powering GHG Reductions Through Technology Advancement*. Toronto, Ontario, Canada.

EPA. 2001. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC. (Available on the Internet at <http://www.epa.gov/globalwarming/emissions/national/download.html>).

Lebean, Steve. Ph.D. 1999. Personal Communication with ICF Consulting. Thixomat, Inc. Ann Arbor, Michigan.

Li, David, PhD. 2000. Letter to Reid Harvey, Air Liquide May 19, 2000.

Norsk Hydro. 1998. *Progress to Eliminate SF₆ as a Protective Gas in Magnesium Diecasting*. Hydro Magnesium, Brussels.

Revankar, Vithal; Baker, Philip; Schultz, Allen H., and Brandt, Helmut. 2000. *A replacement for SF₆: The Magshield System*. Annual World IMA 2000 Magnesium Conference.

Schultz, Allen. 2001. Personal Communication with ICF Consulting. Hatch & Associates. Mississauga, Ontario April 27, 2001.

5. Cost and Emission Reduction Analysis of PFC Emissions from Aluminum Smelters in the United States

5.1 Introduction

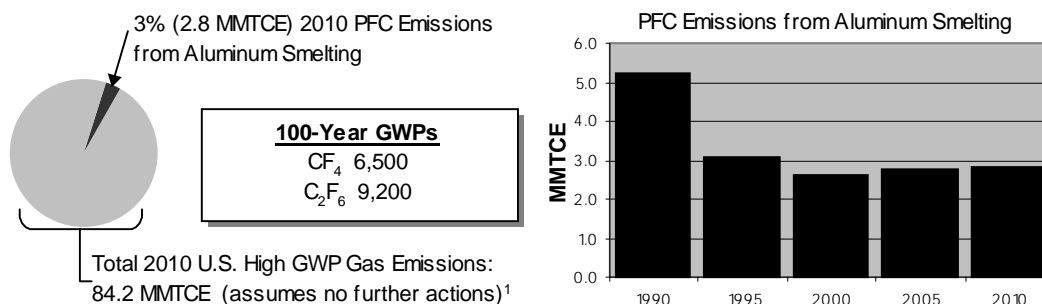
A major source of PFC emissions in the United States is primary aluminum production. Two perfluorocarbons (PFCs) are emitted as a byproduct of aluminum production. These PFCs— CF_4 and C_2F_6 —have 100-year GWPs respectively of 6,500 and 9,200 times the warming potential of carbon dioxide. By 2010, the U.S. would be expected to emit 2.8 MMTCE of PFCs from aluminum production, assuming a business-as-usual scenario in which no further emission reductions are made after 1999 (see Exhibit 5.1).¹ However, as noted below, actual emissions are expected to be lower as a result of voluntary industry efforts in the future.

PFCs are formed as intermittent byproducts during the occurrence of anode effects (AEs). When the alumina ore content of the electrolytic bath falls below critical levels optimal for the aluminum-generating chemical reactions to take place, rapid voltage increases occur. These AEs reduce the efficiency of the aluminum production process, in addition to generating PFCs.

PFC mitigation technologies and practices vary in their availability, cost-effectiveness, and technical feasibility to reduce emissions. Computerized controls and point feeder systems, for example, while capital intensive to implement, are readily available. Other technologies, such as inert anodes, are decades away from potential implementation. In addition, some mitigation technologies may not be applicable to certain production systems, and certain smelters may require expensive retrofits to achieve significant reductions in PFC emissions.

In 1995, the U.S. EPA and 11 out of the nation's 12 primary aluminum companies, with the assistance of

Exhibit 5.1: U.S. Historical and Baseline PFC Emissions from Aluminum Smelting



¹ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

The Aluminum Association, formed the Voluntary Aluminum Industrial Partnership (VAIP). The main goal of this partnership is to reduce PFC emissions while increasing the efficiency of aluminum production. The VAIP sets company-specific PFC emission reduction targets and includes periodic reporting of progress achieved toward those emission reduction goals. VAIP partner companies represented about 94 percent of U.S. production capacity as of 1999. While each company's emission reduction goal is tailored to site-specific conditions, the overall program goal is to reduce PFC emissions from VAIP Partners by 2.2 MMTCE below 1990 levels by the year 2000 (DOS, 1999).

To date, nine countries in addition to the United States have undertaken industry-government initiatives to reduce PFC emissions from primary aluminum production. All of these countries have achieved significant reductions in the rate of PFC emissions. More information on international PFC reduction efforts for each of these 10 countries is available in a document published by EPA in September 1999 (EPA, 1999).

5.2 Historical and Baseline PFC Emission Estimates

EPA estimates PFC emissions from U.S. aluminum manufacturing by summing the product of emission factors (*PFC kg/ton Al*) and activity factors (*tons Al*) for each producer. The historical estimated PFC emissions are reported in the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999 (EPA, 2001). EPA uses production data reported by VAIP partners. For manufacturers that do not report production, national production is apportioned based on smelter capacity of those for which data was not available. National production data and individual smelter capacity data from the U.S. Geological Survey (USGS) for the period 1990 to 1999 was used along with capacity data reported in the Aluminum Statistical Review for 1996 (The Aluminum Association, Inc., 1997).

The emissions are converted to million metric tons carbon equivalent (MMTCE) and summed to present the total PFC emissions for each year. The global warming potentials (GWPs) used in calculating MMTCE were 6,500 and 9,200 for CF₄ and C₂F₆, respectively. The equation used to estimate emissions is presented below.

$$Emissions = \sum_{smelters} ((PFCkg / ton Al) * tons Al)$$

Emission factors for PFC per ton of aluminum are based upon the method found in IPCC/OECD/IEA 1999. The emission factors are estimated by measuring the relationship between smelter operating parameters, such as anode effect frequency and duration, and emissions. For those smelters that did not provide a complete data set required to estimate the process parameters, default parameters from the IPAI Survey (1996 edition) were used. The IPAI survey provides default values for the required parameters by technology type from 1990 to 1993 (IPAI, 1996). For subsequent years, the parameter data was kept constant at 1993 levels, as a conservative and simplifying assumption. Exhibit 5.2 shows historical PFC emissions from aluminum smelting for the years 1990 to 1999.

In order to evaluate the total cost to industry of reducing PFC emissions in 2010, the cost analyses have been conducted using a baseline that reflects emission reductions achieved by VAIP through 1999, but assumes that no additional emission reductions result from the CCAP programs after 1999. Exhibit 5.3 shows estimated baseline PFC emissions through 2010. This projection assumes that U.S. national aluminum production will fall over 110,000 metric tons in 2000, due to announced smelter closings resulting from high prices in wholesale electricity. For 2000 to 2005, production was predicted to grow at an annual rate of 1 percent; for 2005 to 2010, production was predicted to grow at 0.5 percent per year.

No future emission reductions are incorporated into these baseline projections; thus, emission factors are held constant at 1999 levels.

Exhibit 5.2: Historical U.S. PFC Emissions and Aluminum Production from Aluminum Smelting (1990-1999)										
Type of Emissions	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)										
CF ₄	4.6	4.1	3.9	3.4	2.8	2.7	2.8	2.6	2.5	2.4
C ₂ F ₆	0.7	0.6	0.6	0.5	0.4	0.3	0.3	0.3	0.3	0.3
TOTAL	5.3	4.7	4.4	3.8	3.1	3.1	3.2	3.0	2.8	2.7
Emissions (MT)										
CF ₄	2,575	2,310	2,181	1,892	1,560	1,535	1,591	1,488	1,392	1,382
C ₂ F ₆	274	239	226	181	145	138	138	127	117	116
Production (1000 MT)	4,048	4,121	4,042	3,695	3,299	3,375	3,577	3,603	3,713	3,779

Source: EPA, 2001.
Note: Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

Exhibit 5.3: Baseline U.S. PFC Emission Projections from Aluminum Smelting (2000 – 2010)			
Type of Emissions	2000	2005	2010
Emissions (MMTCE)			
CF ₄	2.4	2.5	2.6
C ₂ F ₆	0.3	0.3	0.3
TOTAL (MMTCE)	2.6	2.8	2.8
Emissions (MT)			
CF ₄	1,338	1,406	1,441
C ₂ F ₆	107	112	115

Notes:
Forecast emissions are based on a business-as-usual scenario, assuming no further action.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

5.3 PFC Emission Reduction Opportunities

During an anode effect, carbon from the anode and fluorine from the dissociated molten cryolite bath combine, producing CF₄ and C₂F₆. These gases are emitted from the exhaust ducting system or other pathways from the cell (e.g., the hood of the cell). In general, the magnitude of PFC emissions for a given level of aluminum production depends on the frequency of AEs (# AE) and duration of AEs (*AE duration*). This is shown in the following equations:

$$AE \text{ min/cell-day} = \# AE * AE \text{ duration}$$

$$PFC \text{ kg/ton Al} = S * AE \text{ min/cell-day}$$

$$Emissions = \sum_{smelters} ((PFC \text{ kg} / \text{ton Al}) * \text{tons Al})$$

AE min/cell-day is the total duration (in minutes) of the total number of AEs per day in a given cell. The “S” in the second equation is a positive slope coefficient, specific to the smelter. The coefficient represents the relationship between the operating parameters (e.g., AE minutes and AE frequency) and PFC emissions, and is determined by measuring the composition of the smelter flue gas.

The frequency and duration of AEs depend primarily on the cell technology and operating procedures.

Emissions of CF₄ and C₂F₆, therefore, vary from one aluminum smelter to the next, depending on these parameters. As a result, to reduce PFC emissions each smelter must develop a strategy, which may include some or all of the following measures:

- ***Improving Alumina Feeding Techniques*** by installing point feeders and regulating feed with computer control. Point feeding consists of adding small amounts of alumina—about one kilogram—at various short intervals, usually less than one minute. This is the best alumina feeding method at present, and point feeding is now an important feature in all new cells, as well as in modernization or retrofitting projects for older cell lines.
- ***Using Improved Computer Controls*** to optimize cell performance. These systems monitor the different parameters that contribute to the build-up of AEs. System operators would be alerted before an AE can take place, thus reducing the AE frequency. Improved computer controls can also work in conjunction with point feeders.
- ***Training Cell Operators*** on methods and practices to minimize the frequency and duration of AEs. Also, operators can be trained to maintain strict control over alumina properties and cell operating parameters, and to provide timely and appropriate mechanical maintenance.

5.4 Cost Analysis

For this analysis, smelters in the United States were grouped by technology type (vertical stud Söderberg, horizontal stud Söderberg, sidework prebake, centerwork prebake, point feed prebake) and facilities within each technology type were assumed to upgrade in one of two ways:

- “minor upgrade,” which includes only the implementation of improved computer controls; and
- “major upgrade,” which includes an upgrade to point feed technology and improved computer controls.

The two upgrade options, as applied to the five smelter technology types, would imply ten separate cost and emission reduction options. However, communication with the VAIP Partners indicated that the majority of U.S. smelters have already implemented computer control technologies and further computer improvements will not significantly affect emissions for sidework prebake, centerwork prebake, and horizontal-stud Söderberg smelters. Also, minor and major upgrades for point feed prebake smelters were associated with minimal emission reductions. Therefore, only five upgrade and cost levels have been estimated: a minor upgrade for vertical stud Söderberg smelters and a major upgrade for vertical stud Söderberg, horizontal stud Söderberg, sidework prebake, and centerwork prebake smelters.

Capital costs were estimated for these five upgrade options using information from published sources (IEA, 2000), industry, vendors, and VAIP input. The net costs of an upgrade are calculated by comparing the initial capital investment and the incremental operating cost to the value of the resulting increase in aluminum production. For a minor upgrade at a vertical stud Söderberg smelter, the initial cost is approximately \$4 million and operating costs are approximately \$2 million per year, while the increase in production yields a benefit of over \$2 million per year. Major upgrades are more expensive than minor upgrades, especially for facilities that use older smelter technologies, such as the vertical and horizontal stud Söderberg smelters. The initial investment for a major upgrade ranges between \$60 and \$65 million from Söderberg smelters and \$8 to \$9 million for prebake smelters. Incremental operating costs and the benefit of added production range from \$1 to \$3 million per year for all smelters.

To compare the relative costs and emission reductions for each upgrade option, two values were calculated. First, the cost per ton of emissions reduced was estimated. This “break-even” cost is the

levelized annual cost divided by the amount of PFC emissions reduced. The levelized annual cost equals the net cost of the upgrade option divided by its respective lifetime; and the PFC emissions reduction equals the product of the technology-specific baseline emission factor, the anode effect reduction rate and the percentage of product capacity impacted by the change. The baseline emission factors were taken from published sources (IEA, 2000), and the reduction percentages were provided by the VAIP Partners (The Aluminum Association, Inc., 2001). The emission factors, along with the anode effect reduction percentages and production increases are shown in Exhibit 5.4. The final break-even costs are shown in Exhibit 5.5.

Exhibit 5.4: Baseline PFC Emission Factors and the Benefits of Upgrades

Option	Baseline PFC Emission Factor (TCE/ton Aluminum)	Anode Effect Frequency Reduction	Current Efficiency Increase*
Retrofit-Minor: VSS	1.05	16%	1.0%
Retrofit-Major: SWPB	0.53	50%	1.0%
Retrofit-Major: CWPB	0.27	41%	0.6%
Retrofit-Major: HSS	0.99	43%	0.4%
Retrofit-Major: VSS	1.05	26%	1.0%

Source: EPA estimates and The Aluminum Association, Inc. 2001.

Notes:

Technology types are as follows: PFPB = Point Feed Prebake, SWPB = Side Work Prebake, CWPB = Center Work Prebake, VSS = Vertical Stud Soderberg, HSS = Horizontal Stud Soderberg.

*Current Efficiency is a measure of production output per unit electricity consumed. Increases in current efficiency provide an incremental increase in production. The increase in aluminum production is counted as a benefit and subtracted from the total cost of the upgrade.

Estimates of each upgrades' incremental emission reductions on a national level serve as the second set of calculated comparison values. The incremental reductions are equal to the product of the anode effect reduction percentages reported by the VAIP Partners (Exhibit 5.4), the estimated 1999 technology-specific emission rates, and the increase in production capacity that is estimated to result from each upgrade (Exhibit 5.6). The capacity eligible for each upgrade was provided by the VAIP Partners (The Aluminum Association, Inc., 2001); the percentage of the total capacity that experiences an upgrade was estimated by the EPA.

Exhibit 5.5 summarizes the incremental emission reductions and break-even costs associated with the five upgrade options. The costs of these upgrades range; computer controls are the least expensive, while conversions to point feed systems are more expensive, especially for Söderberg smelters. Overall, reductions of nearly 17 percent of 2010 emissions can be achieved at a maximum cost of \$1 per metric ton of carbon equivalent, and reductions of over 30 percent of 2010 emissions can be achieved at a maximum cost of less than \$10 per metric ton of carbon equivalent. Although it is unlikely that this scenario reflects the exact upgrade decisions that have been made in the past by each smelter, the total aggregate emission reductions under this scenario correspond to current estimates of emission reductions for the U.S. aluminum industry (The Aluminum Association, Inc., 2001).

It is also important to keep in mind that these cost estimates include only the reduction of PFCs. The technologies assessed also affect process CO₂ emissions and energy consumption (roughly 6.7 percent of the total CO₂ equivalent PFC emissions), which, if accounted for in this analysis, would result in lower costs per MTCE reduced.

Exhibit 5.5: Emission Reductions and Cost in 2010

Option	Break-even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate		MMTCE	Percent	MMTCE	Percent
	4%	8%				
Retrofit-Minor: VSS	0.27	0.54	0.03	1.0%	0.03	1.0%
Retrofit-Major: SWPB	0.43	0.77	0.45	15.7%	0.47	16.7%
Retrofit-Major: CWPB	2.50	3.30	0.17	6.0%	0.65	22.7%
Retrofit-Major: HSS	5.23	6.82	0.14	5.0%	0.79	27.7%
Retrofit-Major: VSS	7.25	9.58	0.07	2.5%	0.86	30.2%

Notes:

Technology types are as follows: PFPB = Point Feed Prebake, SWPB = Side Work Prebake, CWPB = Center Work Prebake, VSS = Vertical Stud Söderberg, HSS = Horizontal Stud Söderberg.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

Sums might not add to total due to rounding.

Exhibit 5.6: Capacity Eligible and Capacity that Experiences Upgrades

Option	Capacity Eligible (MT)	Percentage of Capacity that Experiences Upgrade
Retrofit-Minor: VSS	424,647	40%
Retrofit-Major: SWPB	279,000	100%
Retrofit-Major: CWPB	786,143	100%
Retrofit-Major: HSS	403,042	100%
Retrofit-Major: VSS	424,647	60%

Notes:

Technology types are as follows: PFPB = Point Feed Prebake, SWPB = Side Work Prebake, CWPB = Center Work Prebake, VSS = Vertical Stud Soderberg, HSS = Horizontal Stud Soderberg.

5.4 References

The Aluminum Association, Inc. 1997. *Aluminum Statistical Review: 1996.*, Washington, DC; Publication # HR-94-428101.

The Aluminum Association, Inc. 2001. Communication between the Aluminum Association and the U.S. Environmental Protection Agency. "Summary of Survey Questionnaire for Primary Aluminum Plants in the United States." January 2001. Washington, DC.

IEA. 2000. *Greenhouse Gas Emissions from the Aluminum Industry: Greenhouse Gas R&D Programme April 2000*, Cheltenham, United Kingdom; Report # PH3/23.

DOS. 1999. *U.S. Submission on Ways and Means of Limiting Emissions of Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulfur Hexafluoride (SF₆)*. Submitted to the UN Framework Convention on Climate Change (UNFCCC) Secretariat, July 16, 1999. Bureau of Oceans and International Environmental and Scientific Affairs, U.S. Department of State, Washington, DC. (Available on the Internet at http://www.state.gov/www/global/global_issues/climate/990716_unfccc1_subm.html).

EPA. 1999. *International Efforts to Reduce Perfluorocarbon (PFC) Emissions from Primary Aluminum Production*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC; EPA 430-R-99-001.

EPA. 2001. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC. (Available on the Internet at

<http://www.epa.gov/globalwarming/emissions/national/download.html>).

IPAI. 1996. *Anode Effect and PFC Emission Survey: 1990-1993*. International Primary Aluminum Institute, London, U.K.

IPCC/OECD/IEA. 1999. *Good Practice in Inventory Preparation for Industrial Processes and the New Gases* – “PFC Emissions from Aluminum Production.” Draft Meeting Report. Intergovernmental Panel on Climate Change, Organization for Economic Co-operation and Development, International Energy Agency, Washington, DC.

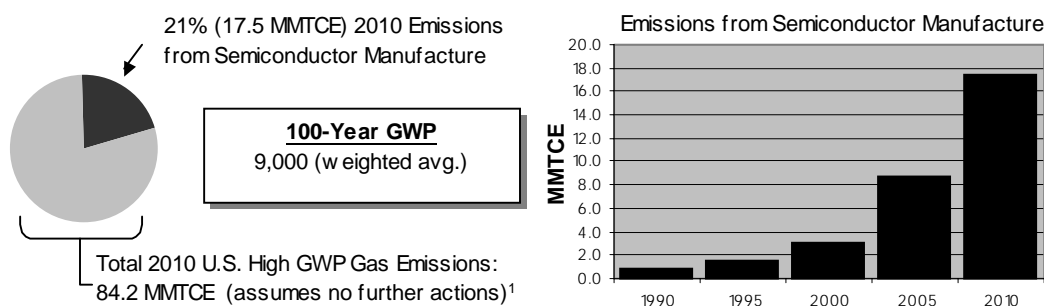
6. Cost and Emission Reduction Analysis of PFC, HFC, and SF₆ Emissions from Semiconductor Manufacturing in the United States

6.1 Introduction

The semiconductor industry uses multiple long-lived fluorinated gases in plasma etching and chemical vapor deposition (CVD) chamber cleaning processes. The gases most often used are trifluoromethane (HFC-23), perfluoromethane (CF₄), perfluoroethane (C₂F₆), and sulfur hexafluoride (SF₆), although other compounds such as nitrogen trifluoride (NF₃), perfluoropropane (C₃F₈) and perfluorocyclobutane (C₄F₈) are also used. The four most common compounds respectively have 11,700; 6,500; 9,200; and 23,900 times the 100-year GWP of carbon dioxide. The weighted industry average of these four is 9,000 based on emissions of each. In the absence of emission control measures, the rapid growth in this industry (historically 15 percent per year in the mid-1990s) combined with the increasing complexity of microchips would be expected to result in increased future emissions of byproducts such as perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and SF₆. While the exact combination of the four above compounds used is specific to the process employed and the type of product being manufactured, the total PFC, HFC, and SF₆ emissions from semiconductor manufacturing in the U.S. is expected to reach over 17 MMTCE by 2010, as shown in Exhibit 6.1.¹ Actual emissions are likely to be much lower as a result of emission mitigation actions by industry, which are not included in this business-as-usual scenario forecast.

In 1996, EPA launched the PFC Emission Reduction Partnership for the Semiconductor Industry. This is a voluntary partnership with U.S. semiconductor producers with the goal of developing ways to reduce the emissions of high GWP gases used in semiconductor manufacture. In 1998, EPA and U.S. manufacturers began working with governments and producers in Europe, Japan, Korea, and Taiwan to develop a global strategy to reduce PFC emissions from semiconductor manufacture. In 1999, the World

Exhibit 6.1: U.S. Historical and Baseline HFC, PFC and SF₆ Emissions from Semiconductor Manufacture



¹ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

Semiconductor Council set a voluntary goal of reducing emissions to 10 percent below 1995 levels by 2010. This voluntary target covers over 90 percent of global semiconductor production. Neither global nor U.S. cost estimates for meeting this target have been completed, but significant investments are expected to meet the goal. Initially, technical innovations introduced by industry are likely to lead to major overall cost reductions in semiconductor manufacturing.

Semiconductor manufacturing is a high growth and rapidly changing industry. Despite this growth, however, total emissions from this industry may peak, according to some reports, by the year 2005 as a result of emission reduction efforts. This represents a substantial reduction in emissions, as much as 50 percent by some estimates, from what would have been released if the industry had expanded production without addressing PFC and other high GWP gas emissions.

6.2 Historical and Baseline HFC, PFC, and SF₆ Emission Estimates

Baseline emissions of high GWP gases from U.S. semiconductor manufacturing were estimated to be 1.5 MMTCE in 1995 (Exhibit 6.2). This estimate was developed based on the approximate sales of the four main gases (HFC-23, CF₄, C₂F₆, and SF₆) to semiconductor firms. Estimates were confirmed with data reported to the EPA by a subset of firms in the industry who have engaged in voluntary emissions reporting efforts. Emissions for the years 2000, 2005, and 2010 were estimated based on projections of historical trends in PFC usage, PFC emissions, and silicon consumption in semiconductor manufacturing, and are presented in Exhibit 6.3.

NF₃ use is rapidly gaining market share in the semiconductor industry for CVD chamber cleaning because of its high process efficiency. Though a greenhouse gas, NF₃ was not listed with a GWP in the IPCC's Second Assessment Report (Molina et al., 1995). This analysis presents options being considered by the semiconductor industry to reduce emissions of greenhouse gases, including NF₃. The business-as-usual estimate includes projected baseline emissions of NF₃. The semiconductor industry uses a broader definition of the term "PFC"—perfluorocompound, rather than perfluorocarbon—and therefore includes NF₃ when referring to PFC emissions. The term "FC" will be used in this section to describe fluorinated compounds used as of 1995 (HFC-23, CF₄, C₂F₆, and SF₆) and NF₃ will be discussed independently, to remain consistent with the remainder of this report.

Exhibit 6.2: Historical U.S. HFC, PFC, and SF₆ Emissions from Semiconductors (1990-1999)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	0.8	0.8	0.8	1.0	1.2	1.5	1.9	1.9	1.9	1.9

Source: EPA, 2001.

Note: Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

Exhibit 6.3: Baseline U.S. HFC, PFC, NF₃ and SF₆ Emissions from Semiconductors (2000-2010)

	2000	2005	2010
Emissions (MMTCE)	3.1	8.7	17.5

Notes:

Forecast emissions are based on a business-as-usual scenario, assuming no further action.

NF₃ was assumed to account for one percent of total emissions from semiconductor manufacturing based on 1995 gas usage.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

6.3 HFC, PFC, and SF₆ Emission Reduction Opportunities

Opportunities to reduce emissions from semiconductor manufacturing fall into the following three categories: CVD cleaning emission reduction technologies (*in situ* dilute NF₃ clean technology and NF₃ remote cleaning technologies), etching emission reduction technologies (plasma abatement, thermal destruction and catalytic destruction) and facility-wide solutions (recapture/recycling and process optimization). Costs (cost-of-ownership) and technical feasibility of implementation vary depending on the products manufactured (product type and size of wafer processed) and the design and age of the fabrication facility (fab). Existing fabs (capable of processing wafers up to 200 millimeters in diameter) may have insufficient infrastructure and space to implement some emission reduction technologies. For new and future planned fabs, purchasing state-of-the-art process equipment (much of which is still in the design phase) that optimizes PFC use and employs alternative chemistries is currently believed to be the least-cost option. The following outlines some of the commercially available or near commercially available technologies.

CVD Cleaning Emission Reduction Technologies

Current and historical semiconductor manufacturing processes use C₂F₆ as the primary dry chamber clean gas. The industry has developed NF₃-based clean recipes that may be used to safely and efficiently clean CVD chambers in place of traditional C₂F₆. Two basic NF₃ clean technologies are currently available—one that introduces NF₃ directly into the CVD process chamber (*in situ*) where the gas is dissociated in a plasma; and another which dissociates NF₃ in a plasma upstream (remote) of the CVD process chamber and sends the active N and F atoms to selectively clean deposited material from inside the chamber. While NF₃ possesses a GWP marginally lower than C₂F₆ (8,000 vs. 9,200), it is the chemical's overall efficiency that leads to the reduced climate impact as compared to C₂F₆, in that less NF₃ is needed to perform the same function and the gas is reacted more fully.

***In situ* NF₃ Clean Technology (Novellus).** *In situ* NF₃ has been demonstrated to achieve emission reductions of greater than 90 percent at all process conditions. A plasma is generated inside the chamber by dissociating the NF₃ molecules, whose products then remove deposits to produce predominantly HF and other compounds that are removed by a facility's acid gas scrubber system.

NF₃ Remote Clean™ Technology (Applied Materials). The Remote Clean™ NF₃ system has been demonstrated to reduce FC emissions from the dielectric chamber cleaning process by over 95 percent. The unit uses an upstream device to dissociate NF₃ using argon gas at a 99 percent efficiency rate. In addition, chamber cleaning times are 30 to 50 percent faster than baseline C₂F₆ clean times (International SEMATECH, 1999). The Remote Clean™ system converts the source gas to active atoms in the plasma, upstream of the process chamber. These electrically neutral atoms can selectively remove material in the chamber. The remote cleaning technology differs from *in situ* technology in that the NF₃ dissociates into plasma before entering the chamber rather than being dissociated inside the chamber. The byproducts of Remote Clean™ include HF, F₂, and other gases, of which all but F₂ are removed by facility acid scrubber systems.

Etching Emission Reduction Technologies

Point-of-Use Plasma Abatement (Litmas). The point-of-use plasma abatement system uses a small plasma source which can be located in the foreline of an etch tool or in the gas line between the process tool and the main pump, thus isolating the tool from the fab's waste stream. This plasma system is located before the dry pump nitrogen purge such that it can access the undiluted exhaust stream. It effectively dissociates the FC molecules, which react with fragments of the additive gas—H₂, O₂, H₂O, or CH₄—in order to produce low molecular weight by-products such as HF with little or no GWP. Wet scrubbers can then remove these product molecules. The presence of additive gas is necessary to prevent later

downstream reformation of FCs (Motorola, 1998). Plasma abatement has been shown to reduce emissions from the etcher by over 97 percent when using water vapor as an additive gas (International SEMATECH, 1998c). The evaluations performed to date indicate no apparent interference with the etch process.

Thermal Destruction/Thermal Processing Units (TPU). This technology can be used to reduce PFC emissions from both the etching and the CVD chamber cleaning process and is advantageous in that it does not affect the manufacturing process (Applied Materials, 1999a). Several commercially available FC thermal destruction systems can effectively abate some FCs, but only a few have been proven to abate all FCs at greater than 90 percent destruction efficiency. In addition, the combustion devices require a combustion fuel and use significant amounts of cooling water that creates wastewater, requiring treatment as industrial waste. Thermal oxidation may also produce NO_x emissions, which are regulated air pollutants.

Catalytic Decomposition System (Hitachi). Catalytic destruction systems are similar to thermal destruction units in that the system is installed in the process after the turbo pump that dilutes the exhaust stream prior to feeding it through the scrubber and emitting the scrubbed gases into the atmosphere. Consequently, there is no back-flow into the etching tool itself, which could adversely affect the performance of the etching tool. Catalytic destruction technologies can reduce FC emissions by 98 percent. However, their design must reflect a minimum concentration and flow of FC within the exhaust stream. Therefore, off-the-shelf systems will work only for facilities with certain stream or process specifications. Because catalytic destruction systems operate at low temperatures, they produce little or no NO_x emissions and have low water demands.

Fab-Wide Solutions

PFC Capture/Recovery. This technology separates unreacted and/or process-generated FCs from other gases for further processing. Currently available capture systems are guaranteed to remove 90 percent of emissions. In general, removal efficiency of C_2F_6 , CF_4 , SF_6 , and C_3F_8 is higher, in the high 90s, while CHF_3 and NF_3 removal efficiencies fall between 50 to 60 percent. For this analysis, an average figure of 90 percent is used (Kelly, 1999). This effluent treatment process allows for the possibility of some recycling or reuse of the captured FC gas (Mocella, 1998). These systems can either repurify the FC for reuse or they can concentrate the gas for subsequent offsite disposal. Semiconductor manufacturing exhaust requires considerable pretreatment to remove materials undesirable to the separation technology. Because current demand for recycled FCs is low, either destruction or reprocessing must be considered (Mocella, 1998). Destruction costs are estimated to be \$3/kilogram. Reprocessing costs are estimated to be significantly more expensive so this option is not considered further here. Although a few companies have installed pilot FC capture/recovery systems, this technology is reported to be unattractive if NF_3 cleaning systems are used because such cleaning processes do not leave sufficient FCs in the stream to make gas recovery economically viable.

Lower GWP Substitutes. This practice has the potential to reduce FC emissions from semiconductor manufacturing by replacing conventionally used FCs with other FCs that yield comparable performance with less potential environmental impact due to lower GWPs, high destruction efficiency, or lower atmospheric lifetimes. For example, in the etching process, the currently used FC C_4F_8 has a GWP of 8,700. In contrast, alternatives such as C_3F_6 and C_5F_8 create approximately equal contact holes and have respective GWPs of 90 and 100. In addition, C_5F_8 has an atmospheric lifetime of one year and a destruction efficiency of greater than 90 percent, versus a lifetime of 3,200 years and a destruction efficiency of about 80 percent for C_4F_8 (Cowles, 1999; Hokari, 1999). These substitutes may have faster or comparable etching rates, increased etching efficiency, and may lead to an overall reduction in amount of FCs used and emitted for each process type. (Varying byproduct emissions—the small fraction of each FC used that is transformed into CF_4 —present an additional concern to be factored into estimates of the

overall potential reductions that may result from substitution.) Although FCs are not completely eliminated in these cases, overall emissions and potential impacts may be lower than in a scenario without the substitution. Because cost estimates are unavailable at this time, this option is not discussed further.

Process Optimization. This practice involves the use of end-point detectors and/or process parameter variation to find the level of optimum FC utilization to reduce excess emissions. For example, optimization using C₂F₆ in the chamber cleaning processes has been reported to reduce consumption by up to 50 percent and to abate up to 85 percent of FC emissions, as well as reduce chamber cleaning times by 15 percent (Deacon 1997, Lagan *et. al.* 1997, McNabb 1997). Because cost estimates are unavailable at the present time, this option is not discussed further.

6.4 Cost Analysis

Cost analyses are conducted for the following options: NF₃ cleaning technologies, plasma abatement, thermal and catalytic destruction, and recapture/recovery. Process optimization and lower GWP substitutes were not considered due to lack of operational test data. Unless otherwise noted, the analyses are based on the assumption that U.S. semiconductor fabs use between 75,000 to 150,000 pounds of FCs per year. Using an emission factor of 0.6 to 0.8 pounds of FCs out for each pound in leads to an annual emissions range of 45,000 to 120,000 pounds per year. For the purposes of this analysis, it is assumed that 60 percent of the emissions are from the chamber cleaning process, and the other 40 percent come from the etching process on a mass basis.

Costs of implementing reduction technologies are fab specific, so they may differ from the information assumed below. A discounted cash flow analysis was performed for each emission reduction option to estimate the price of carbon equivalent that would offset the cost of implementing the emission reduction option using a project lifetime of five years and two discount rates of four and eight percent. Only the higher cost estimates are given for each reduction option to present the highest cost of mitigation scenario. Preliminary estimates of the potential emission reduction for each technology or practice by end use were also developed. These potential emission reductions are expressed as a percent reduction of 2010 baseline emission estimates.

CVD Cleaning Emission Reduction Technologies

NF₃ Remote Clean™ Technology (Applied Materials). The costs and emission reductions for implementing NF₃ cleaning technologies are as follows:

- Total costs equal approximately \$95,000 per tool per year, which includes capital and operations/maintenance (O&M) costs; and
- Emission reductions are estimated to be 5,500 metric tons of carbon equivalent (TCE). The remote clean technology uses approximately 1,400 pounds of NF₃/year, with an emission factor of approximately one percent (GWP 8,000). The business-as-usual cleaning technology would require approximately five times the amount of material by weight, thus replacing approximately 7,000 pounds of C₂F₆/year, with an emission factor of 70 percent (GWP 9,200).

***In situ* NF₃ Clean Technology (Novellus).** There is currently no cost information available on the *in situ* Novellus Clean Technology. However, it is assumed that the cost will be no more expensive than the NF₃ remote cleaning technology. Therefore, the same cost of reduction and market share was used.

Etching Emission Reduction Technologies

Point-of-Use Plasma Abatement (Litmas). The cost and emission reduction estimates for plasma abatement systems assume four chambers per tool and one tool. The costs and emissions reductions are as follows:

- Total costs equal approximately \$24,000 per year, which includes capital, O&M, and installation costs;
- Emission reductions are estimated to be 621 TCE. To estimate the potential reduction, it was assumed that C_2F_6 has a flow of 100 cubic centimeters per minute; and
- An emission reduction of 261 kilograms per year per tool is expected based on the tool running for 650 hours/year with an abatement efficiency of 97 percent (Burton, 2000).

Thermal Destruction System. Currently available destruction systems can be used to reduce emissions. The cost and emission reduction estimates presented here assume 10 systems per facility. The costs and emission reductions are as follows:

- Total costs equal approximately \$2.1 to \$3.1 million per year, which includes capital, O&M, and installation costs; and
- Emission reductions are estimated to be 22,000 to 60,000 TCE.

Catalytic Destruction. Hitachi's catalytic destruction systems are a new technology and cost information was not available to the public. It is believed that the costs will be comparable to thermal destruction systems, but that emissions reduced will be higher by as much as 5,000 TCE.

Fab-Wide Solutions

PFC Capture/Recovery or Recycling System. Although several major gas suppliers have developed pilot PFC recapture/recovery systems, there is currently little or no market for the recovered material. However, in some instances where FCs must be used and NF_3 is not a possible substitute, recapture/recovery systems appear to be a technically viable means of reducing FC emissions. The cost estimate and emission reduction potential of this technology were based on the following assumptions:

- Total costs equal approximately \$1.8 million per year, which includes capital, O&M, and installation costs for two units per facility. Installation costs can vary considerably. One major cost is the installation cost for providing a segregated FC waste stream. For a new fabrication facility, this could range between \$600,000 to \$1,000,000, but could be much more for an older large facility;
- Emission reductions are estimated to be 50,000 to 134,000 TCE;
- Destruction costs are estimated to be \$3/kilogram or approximately \$1.10/TCE;
- Two systems are needed per facility; and
- It is assumed that FC recapture systems could be installed to accommodate up to half of all emissions from semiconductor manufacture. Thus, given the 90 percent average removal rate, up to 45 percent of emissions could be eliminated using FC recapture systems. Similarly, 45 percent could be eliminated by the destruction systems described above. These two options are mutually exclusive; manufacturers would implement either one or the other because using thermal destruction does not leave enough FCs in the stream to make recapture economically viable. As a result, the emission reductions estimated to be attainable from each option cannot be added together.

Results

Exhibit 6.4 summarizes the options for reducing FC emissions from the semiconductor industry, their respective costs, and the associated incremental and cumulative emission reductions. Exhibit 6.5 shows the market assumptions used in calculating the reductions presented in Exhibit 6.4. Fab-wide reductions can be applied to 100 percent of the emissions, while etch and chamber specific reductions can only reduce emissions from their respective percentage of the total emissions. Plasma abatement is believed to be the most popular option in the industry at the moment, so it was given the largest percentage of reductions in the etching sector (55 percent). Recapture/recycling was given five percent of the etching sector and ten percent of the chamber cleaning sector. All other portions were given equal percentages of the remainder in the respective sectors.

Exhibit 6.4: Emission Reduction and Cost in 2010

Option	Break-even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate		MMTCE	Percent	MMTCE	Percent
	4%	8%				
NF ₃ <i>In situ</i> Clean	17.51	18.57	4.7	27%	4.7	27%
NF ₃ Remote Clean	17.51	18.57	4.7	27%	9.4	53%
Plasma Abatement	37.87	41.95	3.8	22%	13.1	75%
Capture/Recycling	39.58	43.99	1.3	7%	14.4	82%
Catalytic Destruction	127.29	141.93	1.4	8%	15.7	90%
Thermal Destruction	138.61	154.54	1.3	7%	17.0	97%

Notes:

2010 baseline emissions from semiconductor manufacture equal 17.5 MMTCE.

Conversion to MMTCE is based on a GWP of 9,000.

Sums might not add to total due to rounding.

Exhibit 6.5: Market Shares Used to Calculate Reductions from Semiconductor Manufacturing

Option	Applicable Process Type	% of Industry to Which the Option can be Applied	% of Industry Process Type Expected to Use the Option	% of Total Reductions Accounted for by Each Option
Capture/Recycling	Fab-wide	100%	8%	8%
Catalytic Destruction	Etching	40%	20%	8%
Plasma Abatement	Etching	40%	55%	22%
Thermal Destruction	Etching	40%	20%	8%
NF ₃ <i>In situ</i> Clean	CVD	60%	45%	27%
NF ₃ Remote Clean	CVD	60%	45%	27%

Notes:

This table assumes that chamber cleaning and etching processes account for 60% and 40%, respectively, of PFC emissions from semiconductor manufacturing.

6.5 References

Applied Materials. 1999. *Catalytic Abatement of PFC Emissions*. Presented at: A Partnership for PFC Emissions Reductions, October 18, 1999, Semicon Southwest 99. Austin, Texas.

Applied Materials. 2000. (Available on the Internet at www.appliedmaterials.com).

Burton, Shep. 2000. Personal communication with ICF Consulting, March, 2000.

Cowles, D. 1999. *Oxide Etch Tool Emissions Comparison for C₅F₈ and C₄F₈ Process Recipes*. Presented at: A Partnership for PFC Emissions Reductions, October 18, 1999, Semicon Southwest 99. Austin, Texas.

Deacon, T. (Applied Materials). 1997. *Proceedings of the SEMICON West 97, "PFC Technical Update," p. D-1 and supplemental materials*. (Available on-line at <http://www.dupont.com/zyron/techinfo/opti.html>).

EPA. 2001. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC; EPA 236-R-01-003. (Available on the Internet at <http://www.epa.gov/globalwarming/emissions/national/download.html>).

Hokari, Y. 1999. *An ASET New Program for PFC Emission Reduction in Dry-Etching Process*. Association of Super-Advanced Electronics Technologies (ASET).

International SEMATECH, 1998c. *Evaluation of a Litmas "Blue" Point-of-Use (POU) Plasma Abatement Device for Perfluorocompound (PFC) Destruction*. Technology Transfer # 98123605A-ENG. (Available on the Internet at <http://www.sematech.org/public/docubase/summary/3605aeng.htm>).

International SEMATECH. 1999. *Motorola Evaluation of the Applied Science and Technology, Inc. (ASTex) ASTRON Technology for perfluorocompound (PFC) Emissions Reductions on the Applied Materials DxL Chemical Vapor Deposition (CVD) Chamber*. Presented at: A Partnership for PFC Emissions Reductions, October 18, 1999, Semicon Southwest 99. Austin, Texas.

Kelly, R.M. 1999. *Praxair's PFC Capture Technology*. Praxair Inc. Presented at: A Partnership for PFC Emissions Reductions, October 18, 1999, Semicon Southwest 99. Austin, Texas.

Lagan, J., et. al. 1997. Proceedings from the SEMI Technical Program, "Perfluorocompound (PFC) Technical Update," SEMICON West, San Francisco. (Summary available on-line at <http://www.dupont.com/zyron/techinfo/opti.html>).

McNabb, J. (Hewlett-Packard). 1997. Proceedings of the SEMICON Southwest 97, "A Partnership for PFC Emissions Reduction" seminar, poster paper session, paper 4. (Summary available on-line at <http://www.dupont.com/zyron/techinfo/opti.html>).

Motorola. 1998. *Long-term Evaluation of Litmus "Blue" Inductively-Coupled Plasma Device for Point-of-Use PFC and HFC Abatement*. Presented at: A Partnership for PFC Emissions Reductions, October 18, 1999, Semicon Southwest 99. Austin, Texas.

Mocella, M.T. 1998. *PFC Recovery: Issues, Technologies, and Considerations for Post-Recovery Processing*. Dupont Fluoroproducts, Zyron Electron Gases Group. (Available on the Internet at <http://www.dupont.com/zyron/techinfo/monterey98.html>).

Molina, Wooldridge and Molina. 1995. *Atmospheric Geophysical Research Letters*. Vol. 22, No. 13.

7. Cost and Emission Reduction Analysis of HFC Emissions from Refrigeration and Air-Conditioning in the United States

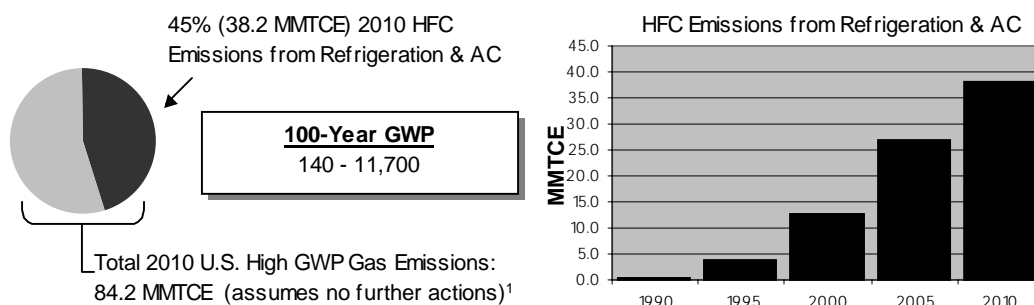
7.1 Introduction

A number of hydrofluorocarbons (HFCs) are used in refrigeration and air-conditioning systems that, when operated and repaired, result in the emission of HFCs. Specifically, emissions occur in product and equipment manufacturing, component failure, leaks and purges during operation, releases during servicing, releases from the disposal of equipment or used refrigerant containers and (illegal) venting of refrigerant. The use of refrigerant and air-conditioning equipment also generates “indirect” emissions of greenhouse gases (primarily carbon dioxide) from the generation of power required to operate the equipment. It is important to note that in many applications, these indirect emissions may outweigh the direct emissions from this sector in the U.S., and hence, gains in energy efficiency can have a major impact on the total emissions of an application. HFCs have global warming potentials (GWPs) that range from 140 to 11,700. The most commonly used HFC refrigerant, HFC-134a, has a GWP of 1,300 and an atmospheric lifetime of 14.6 years. According to the EPA’s Vintaging Model projections, under a business-as-usual scenario the United States would emit about 38 million metric tons of carbon equivalent (MMTCE) of HFCs by 2010 from the refrigeration and air-conditioning sector assuming reduction efforts are not made (see Exhibit 7.1).¹

In the United States, the refrigeration and air-conditioning sector includes nine major end uses:

- household refrigeration;
- domestic air-conditioning and heat pumps;
- motor vehicle air-conditioning (MVAC);
- chillers;

Exhibit 7.1: U.S. Historic and Baseline HFC Emissions from Refrigeration and Air-Conditioning



¹ A fuller explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

- retail food refrigeration;
- cold storage warehouses;
- refrigerated transport;
- industrial process refrigeration; and
- commercial unitary air-conditioning systems.

Each end use is composed of a variety of different equipment types that have historically used ozone-depleting substances (ODS) such as chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs). As the ODS phaseout is taking effect under the Montreal Protocol and Clean Air Act, equipment is being retrofitted or replaced to use HCFC- or HFC-based substitutes. In time, HCFCs are expected to be replaced with HFCs or other alternative refrigerants. A detailed discussion of the end uses that either currently use HFCs or are likely to use them in the near future is provided in Appendix 7.1.

7.2 Historical and Baseline HFC Emission Estimates

The EPA uses its Vintaging Model and data from industry in order to simulate the aggregate impacts of the ODS phaseout on the use and emissions of various fluorocarbons and their substitutes. The model tracks end uses of these gases over a period of 45 years across more than 40 different applications. The model uses the annual “vintages” of new equipment that enter service in each end use as the main driver of gas usage and emissions. The vintage of each type of equipment determines such factors as leak rate, charge size, number of units in operation, and the initial ODS that the equipment contained (see Appendix A for more information).

Commercial and industrial refrigeration and air-conditioning is one of the major end use categories defined in the Vintaging Model to characterize ODS substitute use in the United States. The Vintaging Model data for HFC emissions from 1990-2010 by substitute within the refrigeration and air-conditioning end uses are shown in Exhibits 7.2 and 7.3. The Vintaging Model’s estimates of HFC emissions by end use within the refrigeration and air-conditioning sector for 2000-2010 are presented in Exhibit 7.4.

There are several regulatory programs in place (e.g., CAA §608 and §609 refrigerant recovery requirements) to regulate emissions of ODS substitutes in some applications. These programs are resulting in significant reductions of ODS substitute emissions. These reductions are incorporated in the baseline estimate. The cost analysis evaluates the cost of reducing emissions from this baseline.

HFC emissions are expected to be greatest in the motor vehicle air-conditioning (MVAC) and retail food end uses. Because HFC-134a has been the primary refrigerant used in automobiles manufactured since 1994, and because it is the primary refrigerant used to replace older CFC-12 systems, the amount of HFC emissions in motor vehicle air-conditioning units is expected to rise. Retail food systems are expected to transition at least in part to HFC-134a and HFC-containing blends, and due to certain equipment characteristics, such as their large charge size, often have higher refrigerant emission rates. Cold storage systems also use large charge sizes, but HFC emissions relative to other refrigeration and air-conditioning end uses are not expected to increase significantly. Emissions of HFCs from chillers are relatively low as a result of the continued use of HCFC-123 and the low leak rates of new HFC-134a units. The requirement to recover and recycle refrigerants during service and disposal is expected to reduce emissions across all of the end uses and is reflected in the baseline. Since commercial unitary and residential air-conditioning equipment has yet to transition into HFCs, the emissions of HFCs from these end uses before 2005 are estimated to be relatively insignificant.

Exhibit 7.2: Historical U.S. HFC Emissions from the Refrigeration and Air-Conditioning Sector (1990-1999)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	0.2	0.2	0.4	1.4	2.6	4.0	5.8	7.5	9.4	11.0

Source: EPA, 2000 (for 1990-1998) and EPA estimates (for 1999).

Notes:

Emissions are not broken down by chemical to avoid disclosure of confidential business information.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

Exhibit 7.3: Baseline U.S. HFC Emissions from the Refrigeration and Air-Conditioning Sector (2000-2010)

	2000	2005	2010
Emissions (MMTCE)	12.7	27.0	38.2

Notes:

Emissions are not broken down by chemical to avoid disclosure of confidential business information.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

Forecast emissions are based on a business-as-usual scenario, assuming no further action.

Exhibit 7.4: Baseline U.S. HFC Emissions by Refrigeration and Air-Conditioning End Use

End Use	2000		2005		2010	
	Quantity (MMTCE)	% of Total	Quantity (MMTCE)	% of Total	Quantity (MMTCE)	% of Total
MVACs	7.3	57	15.8	58	16.9	44
Retail Food	2.6	20	4.6	17	9.8	26
Residential A/C	0.1	1	1.4	5	4.6	12
Refrigerated Transport	1.2	9	2.5	9	2.9	8
Chillers	1.1	9	1.5	6	1.4	4
Industrial Process	0.2	2	0.6	2	1.1	3
Commercial A/C	0.0	0	0.3	1	0.9	2
Cold Storage	0.1	1	0.3	1	0.5	1
Other Appliances	0.1	1	0.2	1	0.2	1
Total	12.7		27.0		38.2	

Notes:

About 75% of emissions are from the retail food and motor vehicle air-conditioning sectors.

Sums might not add to total due to independent rounding.

7.3 HFC Emission Reduction Opportunities

HFC emissions from refrigeration and air-conditioning equipment can be reduced through a variety of technology and practice options. Although some of the options considered in this report may be implemented in the baseline in response to the requirements of existing or proposed regulatory programs, many would entail voluntary action by the private sector. Some of the most widely recognized approaches to reduce refrigerant emissions include:

- maintenance and leak detection to reduce refrigerant leakage (required under existing law);
- technician certification (required under existing law);
- increasing recovery, recycling, and reclamation (required under existing law);
- ensuring proper refrigerant disposal (required under existing law); and
- use of alternative refrigerants and refrigeration and air-conditioning technologies (UNEP, 1998).

Reducing Leak Rates

Several different approaches can be used to reduce leak rates (EPA, 1995; EPA, 1998a). Although some of the options available for existing equipment may be impractical for in-place equipment given the difficulty and expense of retrofitting, there are still many available options that are currently used and economically feasible. Some approaches involve reducing joint failures. There are a number of other leak reduction options used in current industry practice, including:

- use of preventive maintenance, including leak detection;
- broader use and improvement of brazing techniques rather than threaded or snap fittings (e.g., use of sufficient silver content, and use of dry nitrogen or other inert gas to avoid oxidation);
- focus on ensuring accessibility to field joints and use of isolation valves, which allow for greater ease of repair;
- focus on proper securing to reduce vibration fractures in the pipe and connections from the compressor and other moving parts of the system;
- repairing or retrofitting high-emitting systems through targeted component upgrades; and
- performing major modifications to the systems.

As can be seen from this list, leak reduction approaches range from simple repairs of short duration to major, long-lasting system repair jobs. Replacement of high-emitting fittings is one of the most technically and economically feasible approaches that can be used to reduce refrigerant leakage. Although leak reduction is already required by law, leak reduction projects could be more extensive, such as the replacement or upgrade of a major system component.

Technician Certification

As required by law, technicians must be certified to purchase CFC and HCFC refrigerants and service refrigeration and air-conditioning equipment. In 1998, EPA proposed extending these regulations to HFC refrigerants as well. By ensuring that technicians receive training in the recovery and recycling of refrigerant, refrigerant emissions will be reduced.

Recovery and Recycling

Recovery and recycling of refrigerant has already helped to decrease emissions of refrigerants during equipment service and disposal in the United States and has led to reductions in HFC emissions. The approach involves use of a refrigerant recovery device that transfers refrigerant into an external storage container prior to servicing of the equipment. Once the recovery process and source operations are complete, the refrigerant contained in the storage container may be recharged back into the equipment, cleaned through the use of recycling devices, sent to a reclamation facility to be purified, or disposed of through the use of incineration technologies. Recycling cleans and reclamation purifies recovered refrigerant; reclamation is more thorough and involves repeated precision distillation, filtering, and contaminant removal. Refrigerant recovery may also be an important way to reduce emissions from near-empty refrigerant containers (i.e., can heels). Refrigerant recovery is widely practiced under EPA regulations pursuant to the Clean Air Act Amendments and is therefore not analyzed further here.

Proper Refrigerant Disposal

One potential source of emissions from the refrigeration and air-conditioning sector in the United States is the accidental venting of contaminated refrigerant. One method to reduce venting of such refrigerant is to increase the reclamation of used refrigerant and properly dispose of the refrigerant that cannot be reclaimed

(UNEP, 1999). The cost to dispose of refrigerant, including transportation and storage, is estimated to be between \$1.50 and \$5.00 per pound, depending on the quantity purchased (ICF Consulting, 2000). Proper refrigerant disposal is required by existing law and is therefore not analyzed further here.

Replacement Options

In addition to the emission reduction approaches that may be required by existing law and EPA regulations, there are several potential ODS replacement options that could be used in place of HFC-containing equipment in the United States. These include secondary loop systems, distributed systems, and ammonia- or hydrocarbon-based systems. Such technological changes may also reduce charge size, which will in turn reduce emissions. Some of these alternative refrigerants and technologies have not been commercialized, but may become more feasible with research and development (Dieckmann and Magid, 1999). Alternative refrigerants and equipment designs are described in Appendix 7.2.

7.4 Cost Analysis

There are technically feasible opportunities for reducing HFC emissions from the refrigeration and air-conditioning sector. It is anticipated that the most cost-effective approaches, including leak reduction, refrigerant recovery, and proper refrigerant disposal, will be implemented under EPA regulatory programs. The main factors affecting the feasibility of implementing certain replacement options include designing new alternative-refrigerant systems that meet the strict requirements for protection of human health and the challenge of designing system components that are compatible with substitute refrigerants (UNEP, 1999). Exhibit 7.5 presents emission reduction technologies and practices. Appendix 7.2 provides additional information on the technical issues associated with developing refrigeration and air-conditioning systems that use non-HFC refrigerants.

The more promising emission reduction opportunities include:²

- Ammonia and hydrocarbon systems and state-of-the-art emission reduction technology are feasible for new industrial process refrigeration systems. For cold storage and retail food systems, replacing existing equipment with equipment that uses non-HFC refrigerants can be quite expensive, although the total emission reduction could be substantial (UNEP, 1999). For these end uses, most emission reduction opportunities for existing equipment will involve focusing on minor and major repairs of high-emitting fittings and faulty components.
- Replacing leaking components and repairing weak joints, as is required by law for large systems, has the potential to reduce HFC emissions to a significant degree, especially in large systems such as chillers, cold storage warehouses, and retail food systems that could leak large amounts of refrigerant. Regular monitoring of refrigeration and air-conditioning systems to check for leaks will prevent the loss of refrigerant. Many efforts to reduce leakage will be made under compliance with proposed regulatory requirements. Voluntary private sector initiatives to reduce leakage further than required under regulation are also feasible.

² One of the more promising replacement options may be the introduction of new refrigerants that can be used in existing HFC systems. Currently, ammonia and hydrocarbons are viable options for certain applications, but for the majority of traditional HFC systems, major design modifications would be required, and in some systems, safety concerns may violate fire codes, negating this as an option entirely. Recently, the EPA Significant New Alternatives Policy (SNAP) program has been considering the acceptability of non-ammonia refrigerant blends that have significantly lower GWPs than the currently available HFCs. However, due to insufficient data, such potential alternative refrigerants were not considered in this analysis.

- Replacing HFC direct expansion systems with HFC distributed systems in retail food settings offers the potential to reduce HFC emissions. Distributed systems have smaller refrigeration units distributed among the refrigerated and frozen food display cases, with each unit sending heat to a central water cooling system. A distributed system would significantly reduce the refrigerant inventory and minimize the length of refrigerant tubing and the number of fittings that are installed in direct expansion systems, thereby reducing leaks of HFCs (Dieckmann and Magid, 1999).
- Designing new retail food and cold storage systems to operate using secondary loops with HFCs or alternative refrigerants such as ammonia can reduce HFC emissions. Secondary loop systems circulate a secondary coolant or brine from the central refrigeration system to the display cases, isolating customers from the refrigerant (UNEP, 1999; Dieckmann and Magid, 1999). These systems have lower leak rates and operate at reduced charges. Other positive features of this technology include longer shelf life, enhanced reliability, more efficient defrost, and less maintenance required than conventional direct expansion systems. Additionally, pipes used in these systems are now pre-manufactured and can be made of pre-insulated plastic instead of copper. This reduces material costs and, by eliminating the need for brazing, allows for faster installation. In recent years, installation costs have been reduced by more than 25 percent. With continued research and development, it is expected that this technology will soon be as cost-effective to purchase, install, and operate as direct expansion systems (Bennett, 2000).
- Several HFC-alternative refrigerants are being researched and developed, including: (1) carbon dioxide or hydrocarbon secondary loop systems in motor vehicle applications; (2) hydrocarbon systems for residential refrigeration equipment; and (3) hydrocarbons in hermetic systems for residential applications.
- Geothermal cooling systems for residential and commercial spaces are becoming increasingly popular and economically sound as an alternative to conventional air-conditioning systems. Geothermal technology transfers heat between the system and the earth and can provide both space heating and cooling. Though installation costs are typically 30 to 50 percent higher than conventional systems, incremental costs are reduced by 20 to 40 percent, due in large part to increased energy efficiency. Economic paybacks can accrue in as little as three to five years. Geothermal systems may save homeowners 20 to 50 percent in cooling costs (Geoexchange, 2000; Rawlings, 2000). Due to lack of cost and market penetration data, this technology is not considered further in this analysis.

Estimating Costs of Reducing HFC Emissions

To develop estimates of the costs of reducing HFC emissions through implementation of the non-regulatory mitigation options, preliminary estimates of incremental capital and operating costs were developed.³ Most of the readily available data focused on the costs and emission reductions for recovery and leak reduction operations.⁴ Using information available for select equipment modification and

³ In some cases incremental cost data are not available given that the technologies have not been commercialized.

⁴ In the United States, substantial reductions in emissions of HFCs from the refrigeration and air-conditioning sector can be achieved at low cost. The most cost-effective approaches include increasing recovery rates and reducing leakage rates. Preliminary data gathered from industry in support of EPA regulatory efforts indicate that leakage rates for certain types of existing equipment range from 8 to 40 percent, whereas achievable leak rates for new or modified equipment can be between 7 to 15 percent. Some experts suggest that through additional design and practice changes, leakage could be reduced to as low as 2 to 5 percent in the future. Recovery of refrigerants during servicing or disposal can be profitable in many cases, especially for equipment with very large charge sizes. Preventing the servicing of motor vehicle air conditioners by individuals that lack the tools and skills to recover refrigerant (also a proposed regulatory requirement), and increasing rates of refrigerant recovery during equipment disposal can also lead to substantial reductions in emission at a relatively low cost.

replacement options, a spreadsheet model was used to estimate the break-even refrigerant price (i.e., the refrigerant price that would offset the investment in the practice or technology to reduce emissions). Specifically, a discounted cash flow analysis was performed for each emission reduction option to estimate the refrigerant price that would offset the cost of the emission reduction option. Then the carbon-equivalent value was determined by subtracting the break-even price from the refrigerant market price and converting to a metric ton of carbon equivalent (TCE) basis. Finally, preliminary estimates of the potential emission reduction for each technology or practice by end use were developed. These potential emission reductions are expressed as a percent reduction of the baseline emission estimates from the Vintaging Model for 2010.

Analysis of Indirect Emissions and Associated Costs. In addition to direct emission reductions that result from decreased leak rates and/or charge sizes associated with alternative technologies and/or refrigerants, emissions during manufacture and from energy use were also factored into the break-even refrigerant price. Emissions during manufacture, including the energy consumed and fugitive emissions, were calculated based on the methodologies described in Appendix A of Dieckmann and Magid (1999).

Information on relative energy efficiency was used to estimate changes in annual energy costs and changes in greenhouse gas emissions that result from an increase or decrease in electricity generation, relative to conventional technologies used in each end use. In calculating indirect emissions, each kilowatt hour (kWh) of energy consumption was assumed to emit the equivalent of 0.64 kilograms (kg) of carbon dioxide, the national average emissions from power plants (Sand *et al.*, 1997). Indirect costs from energy consumption were assumed to be \$0.06/kWh, the average energy cost projected for the year 2010 (EIA, 2000).

Analysis of Net Emissions and Costs. Once direct and indirect emissions were determined, they were factored into net emission and cost calculations accordingly. If indirect emissions exceeded direct emission reductions associated with a given alternative technology and/or refrigerant, the option was not analyzed further. Where net emissions were still achieved, indirect emissions were subtracted out, and additional energy costs were considered in the cost analysis. Similarly, where a particular option resulted in increased energy efficiency and therefore decreased indirect emissions, the associated emission savings were added in, and cost savings were factored into the cost analysis.

A financial screening analysis was also conducted to determine if costs would likely exceed \$200/TCE. Replacement options that resulted in net emission reductions but yielded carbon costs that exceeded \$200 were not considered. These included:

- hydrocarbons in secondary loop for residential applications;
- hydrocarbons in secondary loop for motor vehicle air-conditioning applications; and
- carbon dioxide in motor vehicle applications.

Exhibit 7.5: Cost, Duration, and Applicability of Emission Reduction Options

Technology/Practice Description	Estimated Incremental Cost(\$)	Duration of Emission Reduction (years)	Potential Applicability to End Use Equipment								
			Chillers	Retail Food	Cold Storage Warehouses	Refrigerated Transport	Industrial Process Refrigeration	Commercial Unitary A/C	MVAC	Residential A/C	Household Refrigeration
Practice											
Recovery of refrigerant ^a	10 to 3,000 ^b	1	✓	✓	✓	✓	✓	✓	✓	✓	✓
Minor repair ^c											
Minor leak reduction technology	5 to 275 ^b	1	✓	✓	✓	✓	✓	✓	✓	✓	
Replacement of high-emitting fittings	600	5	✓	✓	✓	✓	✓	✓	✓	✓	
Major repair ^c											
Replacement or upgrade of major system component	800 to 1,400	5	✓	✓	✓	✓	✓	✓	✓	✓	
Major modification of the equipment	6,000 to 12,000	< 7 to 10	✓	✓	✓		✓	✓		✓	
Replacement Options: Alternative Refrigerants											
Replacement with equipment that uses ammonia as refrigerant	-	Lifetime of equipment		✓	✓		✓				
Replacement with system that uses hydrocarbon refrigerant ^d	-	Lifetime of equipment				✓	✓		✓		✓
Replacement with CO ₂ refrigeration ^e	-	Lifetime of equipment				✓			✓		
Replacement Options: Alternative Refrigeration Technologies											
Replacement with distributed system	-	Lifetime of equipment		✓	✓						
Replacement with desiccant cooling system	-	Lifetime of equipment	✓					✓	✓	✓	
Replacement with absorption system	-	Lifetime of equipment	✓				✓	✓		✓	
Replacement with secondary loop system	-	Lifetime of equipment		✓	✓				✓		

Notes:

- Not provided given the variability in state of technology commercialization across the end uses (see Section 7.4).
- ^a Refrigerant recovery will be widely practiced under the requirements of EPA regulatory initiatives.
- ^b The wide range in the estimated incremental cost for these readily-available technologies reflects the fact that a variety of equipment types are being considered in this analysis.
- ^c Many efforts to reduce leakage will be made under compliance with proposed regulatory requirements. Voluntary private sector initiatives to reduce leakage further than required under regulation are feasible.
- ^d Systems that use hydrocarbon refrigerants may technically be used as replacements for the chiller, retail food, and cold storage warehouse end uses, but their large charge sizes raises safety and liability concerns. Therefore, this option was not considered further in this analysis.
- ^e Research and development efforts to design CO₂ systems for stationary equipment (e.g., chillers) are being pursued, but industry experts do not believe that this technology will be a major replacement option within the time period of this analysis.

Although the cost of replacing HFCs with carbon dioxide in motor vehicle applications is greater than \$200/TCE and is not studied further, it is important to note that this option represents a potentially significant reduction opportunity. Furthermore, carbon dioxide in motor vehicle applications may provide other benefits such as improved comfort. This analysis suggests that, by 2010, this application would eliminate 17 MMTCE, equivalent to 44 percent of the total HFC emissions from the refrigeration and air-conditioning sector.

Exhibit 7.6 presents the indirect emissions and net emissions calculated for the three most viable replacement options—distributed systems, ammonia secondary loop systems, and HFC secondary loop systems. The analysis compared these emission reduction technologies to a prototypical technology, the direct expansion (DX) system that uses HFCs. DX systems consume an average of 1,200,000 kWh per year and emit an average of 209 TCE (Dieckmann and Magid, 1999). Incremental capital costs for replacement systems were based on the following data provided by industry experts:

- direct expansion systems (base) = \$200 per ton of cooling capacity to install;
- HFC distributed system = 50 percent more expensive;
- HFC secondary loop system = 20 percent more expensive; and
- ammonia secondary loop system = 75 percent more expensive.

It was assumed that the incremental capital costs for ammonia systems included expenditures for equipment needed to ensure safety. The incremental operating costs only included the net energy requirements and did not cover costs associated with training of technicians and development and updating of safety protocols to handle more hazardous refrigerants such as ammonia.

Exhibit 7.6: Net Annual Emissions and Energy Costs of Replacement Options

	DX System (Base)	Distributed System	Ammonia Secondary Loop System	HFC Secondary Loop System
Charge Size (kg)	1633	408	180	180
HFC Leak Rate (% of charge/yr)	15%	4%	0%	2%
Direct Emissions (kg/yr)	245	16	0	4
Change in Direct Emissions (kg/yr)	N/A	(229)	(245)	(241)
Change in Direct Emissions (TCE/yr)	N/A	(204)	(218)	(214)
Energy Consumption (kWh/yr)	1,200,000	1,100,000	1,400,000	1,400,000 ^a
Indirect Emissions (TCE/yr) ^b	209	192	244	244
Relative Indirect Emissions: Change in Indirect Emissions (TCE/yr)	N/A	(17)	35	35
Total Net Emissions (TCE/yr)	N/A	(221)	(183)	(179)
Net Electricity Cost (\$/yr)^c	N/A	(\$6,000)	\$12,000	\$12,000

Source: Dieckmann and Magid, 1999.

Notes:

^a Recent studies on low-charge refrigeration for supermarkets conducted by David Walker of Foster Miller suggest that secondary loop systems with improved technological features can lead to significant reductions in energy consumption (Walker, 2000a).

^b Assumes a national average emissions factor of 0.64 kg CO₂/kWh (Sand *et al.*, 1997).

^c Assumes that energy costs are \$0.06/kWh.

Based on the analysis, only the distributed system results in a reduction of indirect emissions (of 17 TCE) and an electricity cost savings (of \$6,000/year). Both the ammonia and HFC secondary loop systems require additional energy use, resulting in increased indirect emissions of 244 TCE and increased electricity costs of \$12,000 on a yearly basis. However, it should be noted that recent technological advancements to HFC secondary loop systems have greatly augmented their energy efficiency, though

these technologies are not yet economically competitive. With continued research and development and increased popularity and sales, the costs of this technology are expected to decrease in the near future. The additional energy costs of secondary cooling systems shown in Exhibit 7.6 may be offset by other advantages afforded by these systems, such as decreased maintenance costs, lower refrigerant replacement costs, and longer shelf lives (Walker, 2000b; Bennett, 2000).

Results

Exhibit 7.7 presents preliminary estimates of the costs and emission reductions for the mitigation options considered in this analysis. Exhibit 7.7 does not include costs and emission reductions for mitigation options that are required under regulations. Cost analyses were conducted for the following mitigation options: replacing direct expansion systems with distributed systems; repairing or replacing high-emitting fittings; replacing HFC systems with HFC secondary loop systems; and replacing HFC systems with ammonia secondary loop systems. The cost analyses were performed for four- and eight-percent discount rates, both with a ten-year project lifetime. Exhibit 7.7 summarizes HFC emission reductions by cost per metric ton of carbon equivalent (TCE). As shown, 12 percent of refrigerant emission reductions from the baseline can be achieved in 2010, at costs below \$200 per TCE.

Replacing Direct Expansion Systems with Distributed Systems. This option was assumed to penetrate between 10 and 20 percent of the retail food and between 10 and 20 percent of the cold storage refrigeration markets, at a cost of \$0.02/TCE and \$7.21/TCE for four and eight percent discount rates, respectively. Based on this assumption, incremental emission reductions of four percent of the 2010 baseline are projected, equivalent to 1.5 MMTCE. This represents the most significant cost-effective option for reducing HFC emissions in the refrigeration and air-conditioning sector.

Leak Reduction Options. It was assumed that the various leak reduction options would penetrate 10 percent of the retail food and industrial process markets, and five percent of the chillers, cold storage, commercial air-conditioning, residential air-conditioning, and motor vehicle air-conditioning sector markets. This option is estimated to reduce emissions by 1.2 MMTCE, three percent of the total baseline emissions by 2010, at a cost of \$3.58/TCE and \$5.08/TCE for four percent and eight percent discount rates, respectively.

Replacing HFC System with HFC Secondary Loop System. This alternative was assumed to penetrate 10 to 20 percent of the retail food refrigeration market and 10 to 20 percent of the cold storage refrigeration market. It is estimated to reduce emissions by 1.5 MMTCE, or four percent of baseline emissions by 2010, at a cost of \$62.57/TCE and \$65.30/TCE for four and eight percent discount rates, respectively.

Replacing HFC System with Ammonia Secondary Loop System. This alternative, at a cost of \$98.61/TCE and \$108.67/TCE for four percent and eight percent discount rates, respectively, was estimated to penetrate ten percent of the retail food, ten percent of the cold storage, and ten percent of industrial process refrigeration sectors. This alternative would lead to a one percent incremental emission reduction, or 0.6 MMTCE.

Exhibit 7.7: Emission Reductions and Costs in 2010

Option	Break-even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate		MMTCE of 2010 Base	Percent Reduction from 2010 Base	MMTCE	Percent of Baseline Emissions
	4%	8%				
Replace DX with Distributed System	0.02	7.21	1.5	4%	1.5	4%
Leak Reduction Options ^a	3.58	5.08	1.2	3%	2.7	7%
Replace HFC with HFC Secondary Loop System ^b	62.57	65.30	1.5	4%	4.2	11%
Replace HFC with Ammonia Secondary Loop System ^{b, c}	98.61	108.67	0.6	1%	4.8	12%

Notes:

^a See Exhibit 7.5 for available leak repair options. To be conservative, this analysis used the highest cost option of replacing or upgrading a major system component, with an upper cost range of \$1,400. Emissions are reduced over five years. Potential energy savings associated with leak reduction are not considered in this analysis but may slightly reduce break-even costs.

^b Cost estimate derived from Smithart (2000) and Dieckmann & Magid (1999).

^c Ammonia systems may be feasible for certain new equipment applications in the retail food and cold storage end uses. Range for ammonia system costs is based on estimates provided by Smithart (2000) and Dieckmann & Magid (1999). Estimated incremental costs range from \$50-200/MT of cooling capacity. 2010 baseline HFC emissions from refrigeration and air-conditioning end uses equal 38.2 MMTCE.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

Total might not sum due to independent rounding.

7.5 References

ACGIH (American Conference of Governmental Industrial Hygienists, Inc.). 1999. *Guide to Occupational Exposure Values*.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.). 1993. Ammonia as a Refrigerant: Position Paper. Approved by ASHRAE Board of Directors January 28, 1993. (Available at: <http://www.ashrae.org/about/amm%5Fpaper.htm>).

Atkinson, W. 2000. Review Comments. Mobile Air Conditioning Society (MACS) Worldwide, AZ, March 2000.

Baker, J. 2000. *Vehicle Performance of Secondary Loop Air Conditioning Systems (using flammable refrigerants)*. Proceedings, MACS 2000 Technical Conference and Trade Show, Las Vegas, NV, January 2000.

Baker, J.A. 1998. *Mobile Air Conditioning and the Global Climate – A Summary of the Phoenix Alternate Refrigerant Forum – July 15-18, 1998*. Conference Proceedings from the Earth Technologies Forum (October 1998), pg. 109.

Bennett, C. 2000. Personal communication. Sr. Vice President, Althoff Industries, Inc., IL, December 14, 2000.

Calor Gas Refrigeration. 2000. Care Refrigeration Product Information. (Available on the internet at: <http://www.care-refrigerants.co.uk/html/>).

Cooper, P.J. 1997. *Experience with Secondary Loop Refrigeration Systems in European Supermarkets*. Proceedings of the International Conference on Ozone Protection Technologies (November 1997), pg. 511.

Crawford, J. 2000. Review Comments. Trane Company, WI, March 2000.

Dieckmann, J., and H. Magid. 1999. *Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications*. Final Report to the Alliance for Responsible Atmospheric Policy. Arthur D. Little, Inc., Cambridge, MA; Reference Number 49648.

EIA. 2000. *Annual Energy Outlook 2000*. (Available on the internet at <http://www.eia.doe.gov/oiaf/aeo/>).

Environment Canada. 1998. *Powering GHG Reductions Through Technology Advancement*. Clean Technology Advancement Division, Environment Canada, pp.185-188.

EPA. 1995. *Options for Reducing Refrigerant Emissions from Supermarket Systems*. June 1995. Prepared by ICF Incorporated, Washington, DC.

EPA. 1998a. *Regulatory Impact Analysis: The Substitutes Recycling Rule*. May 18, 1998. Prepared by ICF Incorporated, Washington, DC.

EPA. 1998b. *Composition of Refrigerant Blends*. U.S. Environmental Protection Agency, Stratospheric Protection Division, Washington, DC. (Available on the Internet at <http://www.epa.gov/spdpublic/title6/snap/lists/refblend.html>.)

EPA. 2000. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1998*. April 2000. U.S.EPA #236-R-00-001. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC. (Available on the Internet at <http://www.epa.gov/globalwarming/emissions/national/download.html>.)

Fisher, S.K., J.J. Tomlinson, and P.J. Hughes. 1994. *Automobile Air Conditioning: Energy and Global Warming Impacts of Not-in-Kind and Next Generation CFC and HCFC Alternatives* Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN, pp. 41-47, 92-95.

Geoexchange. 2000. Information on geothermal heat pumps. (Available on the Internet at <http://www.geoexchange.org>.)

Hans Hammer of Audi AG. 1998. Presentation at the SAE Alternative Refrigerants meeting in Phoenix, AZ, July 15-18, 1998.

ICF Consulting. 2000. Data collected from various refrigerant reclaimers, Washington, D.C., September 2000.

Kruse, H. 1996. *The State of the Art of Hydrocarbon Technology in Household Refrigeration*. Proceedings of the International Conference on Ozone Protection Technologies (October 21-23, 1996), pp. 179-188.

Mathur, G.D. 1996. *Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/Isobutane*. Proceedings of the International Conference on Ozone Protection Technologies (October 1996), pp. 835-844.

Paul, J. 1996. *A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook*. Proceedings of the International Conference on Ozone Protection Technologies (October 1996), pp. 252-259.

Rawlings, P. 2000. Personal communication. Geothermal Heat Pump Consortium, TX. December 8, 2000.

SAE. 2000. Conference on Mobile Air Conditioning Technologies. Society of Automotive Engineers, Phoenix, Arizona. Summer 2000.

- Sand, J.R., S.K. Fischer, and V.D. Baxter. 1997. *Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies*. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN, pp. 4, 5, 7, 26, 40-42, 58-61, 73-77, 83-85, 122.
- Smithart, G. 2000. Personal communication. Trane Company, WI, July 1, 2000.
- United Nations Environment Programme (UNEP). 1998. *1998 Report of the Technology and Economic Assessment Panel (Pursuant to Article 6 of the Montreal Protocol)*.
- United Nations Environment Programme (UNEP). 1999. *Report of the TEAP HFC and PFC Task Force, October 1999*.
- Walker, D. 2000a. "Low-charge refrigeration for supermarkets". IEA Heat Pump Centre Newsletter, Vol. 18, No. 1/2000, pp. 13- 16.
- Walker, D. 2000b. Personal communication. Foster Miller, MA, December 15, 2000.
- Wertenbach, J., J. Maué, and W. Volz. 1996. "CO₂ Refrigeration Systems in Automobile Air Conditioning." *Proceedings of the International Conference on Ozone Protection Technologies* (October 21-23), pp. 855-864.

Appendix 7.1: Refrigeration and Air-conditioning End Uses

Household Refrigeration

The household refrigeration end use consists of household refrigerators and freezers. HFC-134a is the primary substitute for CFC-12 in domestic refrigeration units, and most new household refrigerators are manufactured to use HFC-134a. The charge size of a typical household refrigeration unit is 0.32 kilograms, and its expected lifetime is 20 years. There are more than 150 million household refrigerators in the United States, and although this end use is one of the largest in terms of the number of units in use, the charge sizes are small. Because the units are hermetically sealed and rarely require recharging, emissions are relatively low. Since household refrigeration units have very low leak rates, the potential for reducing emissions through leak reduction is small. The retirement of old refrigerators is also not expected to result in significant HFC emissions, as U.S. regulation requires that refrigerants be recovered from appliances before disposal. This regulation is enforced by penalties of up to \$25,000 for disposal companies in violation.

Residential Air-conditioning and Heat Pumps

Residential air-conditioning (window units, unitary air conditioners, packaged terminal air conditioners) and heat pumps are another source of HFC emissions from the residential sector. Most of these units are window units and central air conditioners. The charge sizes of the equipment in this sector tend to be small, on the order of 0.5 to 10 kilograms, and the average lifetime of equipment is 15 years. Residential and commercial air-conditioning is relying exclusively on HCFC-22 as the refrigerant until it is phased out for this use. R-410A (refer to Exhibit 7.8 for blend composition) is expected to replace HCFC-22 in new equipment for most end uses once HCFC-22 is phased out under the Clean Air Act. R-407C is expected to replace HCFC-22 mainly in retrofit applications.

Exhibit 7.8: Composition of Refrigerant Blends		
Blend	Chemical Components	Ratio of Components
R-401A	HCFC-22, HCFC-124 & HFC-152	53:34:13
R-402A	HCFC-22, HFC-125 & propane	38:60:2
R-404A	HFC-125, HFC-134a & HFC-143a	44:4:52
R-407C	HFC-32, HFC-125 & HFC-134a	23:25:52
R-408A	HCFC-22, HFC-125 & HFC-143a	46:7:47
R-409A	HCFC-22, HCFC-124, HCFC-142b	60:25:15
R-410A	HFC-32 & HFC-125	50:50
R-502	CFC-115 & HCFC-22	51:49
R-507A	HFC-125 & HFC-143a	50:50

Source: EPA, 1998b.

Motor Vehicle Air-conditioning

Motor vehicle air-conditioners refer to the air-conditioning systems contained in motor vehicles (i.e., cars, trucks, and buses). The quantity of refrigerant contained in a typical car air-conditioner is approximately one kilogram (typically from 1 to 1.2 kilograms for pre-1994 model vehicles containing CFC-12 systems, and an average of 0.8 kilograms for newer vehicles containing HFC-134a systems) (Atkinson, 2000). The expected lifetime of MVAC units is about 12 years. Refrigerant use in this sector is significant because there are more than 160 million motor vehicles with operational air conditioners in the United States

(Atkinson, 2000). CFC-12 was the refrigerant used in MVACs until 1994, after which all air conditioners installed in new automobiles made the switch to HFC-134a. HFC-134a is also used as a retrofit chemical for existing CFC-12 systems (UNEP, 1998). Currently, there are an estimated 50 million vehicles that still operate using CFC-12 refrigerant (Atkinson, 2000). A variety of HCFC/hydrocarbon refrigerant blends are approved as replacements for CFC-12 in motor vehicle air-conditioners, but these blends have captured only a small and declining share of the retrofit market. Possible alternatives to HFC-134a systems include transcritical carbon dioxide systems and flammable hydrocarbon or HFC-152a systems, which are both under study and development (SAE, 2000).

Chillers

Chillers are used to regulate the temperature and reduce humidity in offices, hotels, shopping centers, and other large buildings. The three primary types of chillers are centrifugal, reciprocating, and screw— each of which is named for the type of compressor employed. Chillers are long-lasting relative to most air-conditioning and refrigeration equipment. Most operating chillers will remain in service for more than 20 years and some will last 30 years or more. The charge size of a chiller ranges from 25 (reciprocating) to 1,800 kilograms (centrifugal). Large capacity centrifugal and screw chillers account for over 150,000 units in the United States (EPA, 1998a). HCFC-123 is the refrigerant of choice both for use in new low-pressure chillers and as a retrofit option for existing CFC-11 units. Production of HCFC-123 will continue until 2030, and recycled and recovered amounts will continue to be used thereafter. The market of CFC-12 high-pressure chillers is being replaced by HFC-134a. New chillers using HFC-134a are commercially available and the market for these machines has been very strong. HFC-245fa is a potential refrigerant for use in new low-pressure chillers to replace HCFC-123, and possibly in high-pressure chillers, to replace HFC-134a. However, commercialization of this technology is not likely to occur in the next ten years or so. High-pressure chillers that currently use HCFC-22 will be replaced by several HFC refrigerant blends and HFC-134a chillers. Likewise, most existing CFC-114 chillers will be replaced with new HFC-236fa chillers, for use primarily in specialty applications on ships, submarines, and nuclear power plants.

Retail Food Refrigeration

Retail food refrigeration includes refrigerated equipment found in supermarkets, convenience stores, restaurants, and other food service establishments. This equipment includes small reach-in refrigerators and freezers, refrigerated display cases, walk-in coolers and freezers, and large parallel systems. Charge sizes range from 6 to 1,800 kilograms, with a lifetime of 15 to 20 years. There are about 1.6 million retail food refrigeration systems in the United States (EPA, 1998a). Convenience stores and restaurants typically use stand-alone refrigerators, freezers, and walk-in coolers. In contrast, supermarkets usually employ large parallel systems that connect many display cases to a central condensing unit by means of extensive piping. Because the piping required for connection of all the cases can be miles long, these systems contain very large refrigerant charges.

During the earlier phases of the CFC phaseout, the use of HCFC-22 in retail food refrigeration was expanded considerably. Today, most existing retail food equipment is retrofitted with HCFC-based blends, although HFC blends are also used. New retail food equipment uses HFC blends such as R-404A and R-507A (see Exhibit 7.8).

Cold Storage Warehouses

Cold storage warehouses are used to store meat, produce, dairy products, and other perishable goods. There are about 2,000 cold storage warehouses in the United States. The expected lifetime of a cold storage warehouse is 20 to 25 years, and charge sizes are about 4,000 kilograms. New warehouses that would have used CFC-12 and R-502 as the refrigerant are expected to use HCFC-22 and HFC-134a as

replacements in new equipment. Eventually, R-404A and R-507A are expected to replace HCFC-22 in new warehouses upon implementation of the HCFC phase-out (see Exhibit 7.8). Existing CFC-12 cold storage warehouses can be retrofitted with R-401A as a replacement refrigerant, and existing R-502 warehouses can be retrofitted with R-402A. Not all cold storage warehouses currently use CFCs or their replacements.

Refrigerated Transport

The refrigerated transport end use includes refrigerated ship holds, truck trailers, railway freight cars, and other shipping containers. This end use is one of the smallest because the average charge sizes are relatively small (7 to 8 kilograms) and less than one million refrigeration units are currently in use. The expected lifetime of a refrigerated transport system is 12 years. Trailers, railway cars, and shipping containers are commonly charged with HFC-134a, R-404A, and HCFC-22 (UNEP, 1999). Ship holds, on the other hand, rely on HCFC-22 (UNEP, 1999) and ammonia. In addition to HFC-134a, R-404A can also be used in new equipment (see Exhibit 7.8). Existing equipment can be retrofitted with R-401A and R-404A. In addition, transport refrigeration equipment includes systems that operate based on the evaporation and expansion of liquid carbon dioxide or nitrogen.

Industrial Process Refrigeration

Industrial process refrigeration includes complex, often custom-designed, refrigeration systems used within the chemical industry, petrochemical industry, pharmaceutical industry, oil and gas industry, metallurgical industry, and sports and leisure facilities. Charge size ranges on average from 650 to 9,100 kilograms, and average lifetime is 25 years. There are approximately 7,000 industrial process refrigeration systems in the United States (EPA, 1998a). Ammonia, hydrocarbons, HCFC-123, and HFC-134a are expected to be the most widely used substitute refrigerants for new equipment (UNEP, 1999). Upon completion of the HCFC phaseout, HFC-134a is expected to be the primary refrigerant.

Commercial Unitary Air-conditioning

Commercial unitary air-conditioning systems have relatively small charge sizes of about 9.5 to 34 kilograms. The expected lifetime of a commercial unitary air-conditioning unit is 15 years. There are approximately 2.5 million commercial unitary air-conditioning units in use in the United States (EPA, 1998a). R-407C, R-410A, and HFC-134a are expected to be the refrigerants used to replace HCFC-22 in new equipment upon implementation of the HCFC phaseout in the United States (see Exhibit 7.8).

Appendix 7.2: Alternative Refrigerants and HFC Emission Reduction Technologies

Alternative Refrigerants

Ammonia. Ammonia, primarily used in water cooled chillers, has excellent thermodynamic properties and can be used in many types of systems. In addition, it has the advantage of having a strong odor, which makes refrigerant leaks easier to detect, and is lighter than air, facilitating dispersion in the event of a release (UNEP, 1999). However, it must be used carefully, because it is toxic and slightly flammable. Ammonia is an explosion hazard at 16 to 25 percent in air, which creates a problem in confined spaces. Chillers using ammonia as a refrigerant are commercially available in Europe, and they have efficiencies that are comparable to or better than those of HFC-134a chillers. However, building and fire codes restrict the use of ammonia in the urban areas of the United States and many other countries. These safety concerns and institutional barriers effectively limit the potential for expanded use of ammonia chillers (Sand *et al.*, 1997).

While the use of ammonia within public spaces such as supermarkets is limited in the United States by building codes and ordinances, it is a potential alternative for supermarkets if safety concerns can be adequately addressed through engineering design such as secondary loops and isolation. Indeed, modern ammonia systems in the United States are fully contained closed-loop systems with fully integrated controls that regulate pressures throughout the system. Also, all systems are required to have an emergency diffusion system and a series of safety relief valves to protect the system and its pressure vessels from over-pressurization and possible failure (ASHRAE, 1993). Systems with ammonia are being built and used in Europe (Sand *et al.*, 1997). However, the further use of ammonia as a supermarket primary refrigerant may be unlikely in the near future in the United Kingdom and other countries because of the capital costs and issues of compliance with standards and safety regulations (Cooper, 1997). Ammonia would also be an option in some industrial process refrigeration, contingent upon addressing all of the relevant concerns regarding flammability and toxicity.

The chemical properties of ammonia make it incompatible with current designs of residential light commercial unitary air-conditioning systems, which use copper for the refrigerant tubing, in the heat exchangers and in other components. Ammonia in the presence of water cannot be used with copper or zinc (UNEP, 1999); however, ammonia can be used in aluminum and steel systems. Compatible components would have to be developed to use ammonia. As a result of these technical and cost barriers, as well as ammonia's flammability and toxicity, ammonia is considered an unlikely candidate for use in commercial residential unitary equipment (Sand *et al.*, 1997).

Hydrocarbons. Hydrocarbons have thermodynamic properties that make them good refrigerants; however, their high flammability causes concern for safety. Considering technical requirements only, there is potential for use of hydrocarbons in retail food refrigeration, transport refrigeration, household refrigeration, residential air-conditioning, mobile air-conditioning, and commercial unitary systems. Currently used refrigerants include HC-600a, HC-290, and HC-1270 (UNEP, 1999). In addition to good thermodynamic properties, hydrocarbons also have other advantages such as high energy efficiencies, zero ODP, and very low direct GWP.

The primary disadvantage of hydrocarbons is flammability, resulting in significant safety and liability issues. This causes increased costs for safety precautions in factories and can necessitate design changes in every application, such as relocation of electrical components to reduce the likelihood of accidents from potential leaks (Kruse, 1996; Paul, 1996). This also entails additional hardware costs for many applications (Dieckmann and Magid, 1999; Crawford, 2000). Hydrocarbon refrigerant use is generally restricted by

U.S. safety codes, and with the exception of industrial refrigeration, the EPA has not listed flammable refrigerants as acceptable substitutes to ODS. EPA will not list flammable refrigerants as acceptable for use in existing motor vehicle air conditioners that were not designed to operate with flammable refrigerants unless such use is supported by a thorough risk assessment. Systems that are designed to use hydrocarbon refrigerants can be listed, but liability concerns remain. Systems using flammable refrigerants will require additional engineering and testing, development of standards and service procedures, and training of manufacturing and service technicians before commercialization. Despite these barriers, several refrigerant blends that contain a small percentage (typically less than five percent) of hydrocarbons, and are therefore not flammable, have been approved for use in motor vehicle air conditioners under EPA's SNAP program. In fact, full implementation of hydrocarbons for use in refrigeration requires fewer technical breakthroughs than carbon dioxide systems (see below). Some companies outside the United States have already begun testing hydrocarbons as refrigerants in automotive applications, and it is estimated that systems with flammable refrigerants could be installed in vehicles in as little as four to five years (Mathur, 1996; Baker, 2000).

Although sufficient information is not yet available to fully assess the feasibility of hydrocarbons in large charge sizes for non-mobile vehicle air-conditioning applications in the United States, hydrocarbon refrigerants are already being used in other countries. One company in the United Kingdom has developed four different blends of hydrocarbon refrigerants (composed of isobutane, propane, and ethane) for use in new household refrigerators and freezers, small commercial refrigeration and air-conditioning systems, as well as commercial air-conditioning and commercial and industrial systems that have traditionally used R-502 or HCFC-22. One Swedish company, the world's largest industrial refrigeration company, is now using these hydrocarbon refrigerants in a full range of hydrocarbon chillers, with over 50 different models already available on the market. The new chillers require 60 percent less refrigerant charge than with HFCs. Similarly, one of Europe's largest refrigerator manufacturers has also converted its U.K. factory to use these hydrocarbon refrigerants, with 12 models of refrigerators, freezers, and refrigerator freezers now on the market. There are now over 30 million hydrocarbon refrigerators in use in Europe (Calor Gas Refrigeration, 2000).

Carbon Dioxide. Another option is to use carbon dioxide as a cooling agent. Carbon dioxide has been investigated for use primarily in mobile air-conditioning systems and refrigerated transport. Carbon dioxide is advantageous for use as a refrigerant because it has zero ODP, a low GWP, and is generally available at a 20 percent greater cost than conventional systems (Hans Hammer of Audi AG, 1998; Baker, 1998).

Carbon dioxide has disadvantages as well, and certain issues such as safety (OSHA's recommended 8-hour time-weighted average is 5,000 ppm), cost of designing and purchasing equipment, potential loss of operational efficiency and the associated increase in indirect emissions, refrigerant containment, long-term reliability, and compressor performance would be of concern (Environment Canada, 1998; ACGIH, 1999).

Transcritical carbon dioxide systems are under study and development by many vehicle manufacturers in co-operation with global component and system suppliers. They require substantial new engineering and testing efforts, with emphasis on reliability testing (Wertenbach, 1996). New equipment and technician training would also be required to safely repair systems with operating pressures up to 6 times higher than systems with HFC-134a. The first systems could be available within four to seven years (Baker, 2000).

Alternative Refrigeration Technologies

Secondary Loop Systems. Secondary loop systems pump cold brine solutions through a second set of loops away from the refrigeration equipment and into areas to be cooled. These systems require a significantly lower refrigerant charge, have lower leak rates, and can allow the use of flammable or toxic refrigerants. Secondary loops may be used in commercial and industrial refrigeration applications, for

example, to cool supermarket display cases without circulating toxic or flammable refrigerants throughout the store. The primary disadvantage of the secondary loop system is a loss of energy efficiency. Installers of secondary cooling systems suggest that decreased charge sizes, decreased leak rates, lower maintenance needs, and longer shelf lives can all result in significant cost-savings over time (Bennett, 2000). Indeed, the reduction in size and leak rate of the refrigerant charge could result in a reduced global warming impact, even with the use of fluorocarbon refrigerants. The use of zero GWP refrigerants could result in even lower global warming impacts (Sand *et al.*, 1997). Recent work by the EPA's Office of Research and Development is also showing that because the refrigerating fluid does not go through a phase change, temperature control in the refrigerated cases becomes easier. This represents an important advantage over conventional systems since recent regulations on temperature control for refrigerated products such as meat, poultry, and fish have become more stringent. Moreover, recent technological improvements to secondary cooling systems, such as high-efficiency evaporative condensers and display cases with high temperature brines, have increased system efficiency. Such state-of-the art systems are commercially available, but only at a large cost premium (Walker, 2000a,b). Secondary loops also have potential applications in motor vehicle air-conditioning and residential unitary end uses.

Distributed Systems. Distributed systems are most commonly used in retail food refrigeration, but have potential applications in a variety of end uses (e.g., motor vehicle air-conditioning). A distributed system consists of multiple compressors that are distributed throughout the store near the display cases they serve and are connected by a water loop to a single cooling unit that is located on the roof or outside of the store. Refrigerant charges for distributed systems can be smaller than the refrigerant charge used in a comparable traditional direct expansion system. Significant reductions in total global warming impact from current levels might be possible with distributed systems that use HFC refrigerants (Sand *et al.*, 1997). Reduced refrigerant charge sizes, in addition to increased energy efficiency associated with such systems, could effectively decrease global warming impacts, even with the use of fluorocarbon refrigerants.

Absorption Chillers. Gas-fired (as opposed to electrically powered) absorption water chillers are sold in the United States and are common in Japan where electricity costs are high and waste energy is available. Although absorption chillers are far less efficient than competitive systems if waste heat is not available, the technology is feasible and, under some economic circumstances, compares favorably with centrifugal chillers using fluorocarbon refrigerants. Market success will be determined by factors such as the relative costs of natural gas and electricity (these units are rarely cost-effective without low natural gas prices or high electricity rates and significant amounts of available waste heat), peak load charges, and purchase costs. In addition, absorption chillers currently have higher capital costs than vapor compression equipment, so significant operating cost savings would be necessary to make their purchase economically competitive. Three United States heating, ventilation, and air-conditioning (HVAC) companies are developing direct-fired, triple-effect absorption concepts that are expected to be 20 to 45 percent more efficient than current double-effect chillers (Sand *et al.*, 1997).

Absorption Refrigeration. More than a million thermally-activated ammonia/water absorption refrigerators are manufactured and sold annually worldwide. The refrigerants used for absorption refrigeration have negligible GWP. Absorption refrigeration may become more common in the residential refrigeration end use as ozone-depleting substances are phased out. Absorption refrigeration is commonly used in hotel rooms and for recreational vehicles because it operates quietly and has the ability to use bottled gas as an energy source. Absorption refrigerators are limited in size because of design constraints. The thermal coefficient of performance (COP) of these refrigerators can be increased by as much as 50 percent (from a COP of 0.2 to 0.3) through design improvements without degrading cooling capacity (Sand *et al.*, 1997). Low efficiency and inherent design limitations make it unlikely that absorption refrigeration will become a significant replacement for vapor compression refrigerators. However, absorption refrigeration has great capacity and operating attributes that permit it to fill niche markets (Sand *et al.*, 1997).

Absorption Heat Pumps. Research and development efforts are attempting to create absorption heat pumps that would be used for heating and cooling in residential and light commercial applications. In Europe and the United States, generator absorber heat exchange (GAX) ammonia-water absorption heat pumps are being developed, while field test units have been built in Japan. Absorption heat pumps could be used to reduce global warming impacts in areas where heating load dominates, although they would have the opposite effect in areas where cooling dominates (Sand *et al.*, 1997).

Desiccant Cooling. Desiccant cooling is produced by removing moisture from an air stream using a desiccant, and then separately cooling the dry air. The desiccant is thermally regenerated, typically by burning natural gas or alternatively, by capturing excess heat. Desiccant cooling may replace the latent cooling done by some equipment end uses, such as chillers and motor vehicle air-conditioners. Integrated desiccant cooling systems that combine a desiccant system with a vapor compression or other cooling systems have been successfully installed in some commercial buildings (Fisher *et al.*, 1994). Current designs are used primarily in niche markets that require precisely-controlled and/or low humidity, such as supermarkets and hospital operating rooms. For desiccant-based systems to be considered feasible options in the commercial air-conditioning market, improvements in efficiency, cost, size, reliability, and life expectancy must be made (Sand *et al.*, 1997).

Desiccants require an intermittent source of heat. Because new automobiles are energy efficient, very little waste heat is produced. While an automobile is not moving in traffic or is driven slowly, not enough heat may be produced for a desiccant system to function. Desiccant systems may therefore only be feasible where there is a large heat source, as in a large truck or bus (Environment Canada, 1998). In order for desiccant air-conditioners to become viable options for motor vehicle air-conditioning, it must be demonstrated that adequate waste heat is generated during vehicle operation to drive the system, or an auxiliary burner must be made available when additional heat is required. Current prototypes are large and heavy, such that the desiccant air-conditioning systems must be reduced in size and weight and it must be shown that the systems are durable and can have a service life long enough to justify the initial investment. Finally, costs need to be competitive with HFC compression air-conditioning systems (Fisher *et al.*, 1994).

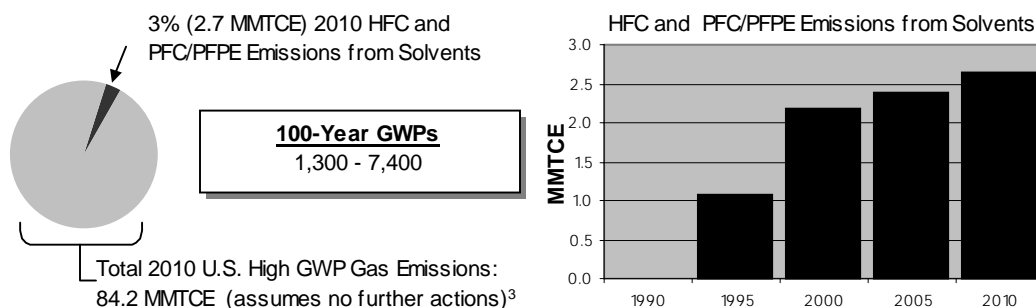
8. Cost and Emission Reduction Analysis of HFC and PFC/PFPE Emissions from Solvents in the United States

8.1 Introduction

Historically, CFC-113, carbon tetrachloride, and methyl chloroform have been used as solvents in the United States for a wide range of cleaning applications including precision, electronics, and metal cleaning (UNEP, 1999) (see Appendix 8.1). The solvent industry has phased out most of its ozone-depleting substance (ODS) use and continues to research alternative cleaning practices and replacement solvents. These alternatives generally offer economic, health, and environmental benefits.

The vast majority of the market, primarily the metal and electronics cleaning end-uses, no longer uses high ozone depleting potential (ODP), high GWP compounds like CFC-113, methyl-chloroform, perfluorocarbons (PFCs), and perfluoropolyethers (PFPEs). Instead, they use alternative technologies such as no-clean, aqueous and semi-aqueous cleaning; and solvents such as hydrofluorocarbons (HFCs), hydrofluoroethers (HFEs), hydrocarbons, and alcohols.¹ Although climate impact is still a concern using some of these substances, these replacement technologies are considered advantageous. Certain solvent applications, however—particularly precision cleaning end uses—require the use of hydrochlorofluorocarbons (HCFCs) such as HCFC-141b and HCFC-225 ca/cb (prior to the HCFC phaseout), and to a lesser extent PFC/PFPEs as replacements because these solvents have high reliability, excellent compatibility, good stability, low toxicity, and selective solvency.² Projected HFC and PFC/PFPE emissions from precision cleaning end uses dominate the greenhouse gas impact from the solvents sector (see Exhibit 8.1).³

Exhibit 8.1: U.S. Historical and Baseline HFC and PFC/PFPE Emissions from Solvents



¹ HFC-4310mee is the most common HFC used in solvent cleaning in the United States. This report makes use of the broader term HFC to refer to several alternatives used in different industries, including HFC-4310mee, HFC-365mfe, a cyclic HFC, and HFC-245fa.

² PFC/PFPEs is a term used to describe a diverse collection of perfluorocarbons (PFCs) and perfluoropolyethers (PFPEs) employed for solvent applications.

³ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

The relatively low boiling points (50-90°C) of HFCs and PFC/PFPEs contribute to their rapid volatilization; the resulting greenhouse gases have 100-year GWPs ranging from 1,300 to 7,400⁴ times the warming potential of carbon dioxide. In the absence of further reduction efforts, under a business-as-usual scenario, the U.S. is projected to emit 2.65 MMTCE of HFCs and PFC/PFPEs by 2010 from solvent applications.

8.2 Historical and Baseline HFC and PFC/PFPE Emission Estimates

Historic emissions from precision cleaning solvents were estimated to be 2.1 MMTCE in 1999 as presented in Exhibit 8.2. This estimate was made using EPA's Vintaging Model, discussed in detail in Appendix A. Although EPA's model is a comprehensive approach, uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emission profiles that were used to estimate annual emissions for various compounds. Projections for the years 2000, 2005, and 2010 were calculated using the same model, assuming 100 percent market penetration of alternative solvents by 2015 (see Exhibit 8.3).⁵ There are several regulatory programs (e.g., Significant New Alternatives Policy Program determines the acceptability of substitutes to ODS) in place to limit use of ODS substitutes in some applications. These actions are expected to result in significant reductions in ODS substitute emissions. These reductions are incorporated in the baseline estimate of emissions. The cost analysis presented here evaluates the cost of reducing emissions from this baseline.

Exhibit 8.2: Historical U.S. HFC and PFC/PFPEs Emissions from the Solvent Sector (1990-1999)										
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	0.0	0.0	0.0	0.0	0.2	1.1	2.0	2.0	2.1	2.1

Source: EPA, 2000 (for 1990-1998) and EPA estimates (for 1999).
Notes:
Emissions are not broken down by chemical to avoid disclosure of confidential business information.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the report.

Exhibit 8.3: Baseline U.S. HFC and PFC/PFPEs Emissions from the Solvent Sector (2000-2010)			
	2000	2005	2010
Emissions (MMTCE)	2.2	2.4	2.7

Notes:
Forecast emissions are based on a business-as-usual scenario, assuming no further action.
Emissions are not broken down by chemical to avoid disclosure of confidential business information.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the report.

⁴ 7,400 is used in this report as the GWP for PFC/PFPEs; it is derived from the respective GWPs of the compounds in this group.

⁵ Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates are made using analytical tools such as the EPA Vintaging Model.

8.3 HFC and PFC/PFPE Emission Reduction Opportunities

HFC and PFC/PFPE emissions from the solvents sector can be eliminated or mitigated through several technologies and practices as presented in Exhibit 8.4. The emissions and uses of these compounds can be further reduced by retrofitting equipment and improving containment of the solvents, initiating recycle and reuse programs, and introducing carbon adsorption technologies. Ongoing research continues to identify low GWP alternatives that could replace high GWP PFCs and HFCs. Certain HFCs and PFC/PFPEs are currently essential to carrier fluid and precision cleaning applications where compatibility of the alternatives is an issue. Four approaches for solvent emission reduction are summarized below (March Consulting Group, 1998 and 1999; UNEP, 1999):

- improved solvent system designs;
- recycle and recovery;
- alternative cleaning technologies; and
- alternative cleaning solvent fluids.

Improved Equipment and Cleaning Processes Using Existing Solvents

Engineering controls, improved containment, and other abatement technologies represent methods for reducing emissions of PFCs and HFCs while new chemicals and technologies are being evaluated. Improved engineering controls include increasing freeboard height, installing freeboard chillers, and using automatic hoists (UNEP, 1999; ICF Consulting, 1992). Likewise, for some applications where adaptations of other types of cleaning processes are not feasible, there are significant opportunities to reduce emissions of solvents during the cleaning process. By improving the design of the solvent bath enclosure and of vapor recovery condensing systems, for example, it is possible to minimize evaporative losses (March Consulting Group, 1998 and 1999). Work is also underway to develop processes that do not require solvents with ODPs or high GWPs.

Exhibit 8.4: Overview of Solvent Technologies Used Worldwide

	Applicability to End-Use		
	Metal	Electronics	Precision
Solvent Classes			
Chlorinated Solvents	✓	✓	✓
HCFC Solvents (HCFC-225 ca/cb and HCFC-141b)		✓	✓
HFC-4310mee	✓	✓	✓
PFC/PFPE Solvents			✓
HFE Solvents	✓	✓	✓
Hydrocarbons	✓	✓	✓
Alcohol solvents	✓	✓	✓
Brominated Solvents	✓	✓	✓
Methyl Siloxanes	✓	✓	✓
Alternative Cleaning Technologies			
Aqueous Cleaning	✓	✓	✓
Semi-Aqueous Cleaning	✓	✓	✓
No-Clean Processes	✓	✓	
▪ Low-solids flux or paste			
▪ Inert Gas Soldering			

HFC and HFE prices are much higher than those of CFC-113 and HCFC-141b, which results in significant improvements in the containment technology of degreasers, defluxers, and dryers. Some cleaning equipment using HFC solvents are being retrofitted with higher freeboard and low-temperature secondary cooling coils. Also, in some cases, other improvements have been made to reduce drag-out losses of solvent from these systems to a very low level. In cases where certain HFCs and PFC/PFPEs are essential solvents in precision cleaning end uses, it is possible to reduce emissions to a minimum level by implementing good handling practices (UNEP, 1999).

Recycle and Recovery

In instances where HFCs and PFC/PFPEs continue to be used for performance reasons, the emissions can be minimized by implementing recycle and reuse programs (UNEP, 1999). Used solvent may be recovered through a distillation process that can take place in either the degreasing unit or the solvent still (Clement *et al.*).

Solvent recovered from electronics applications cannot be recycled indefinitely because reclaimed solvent would not have the same composition as the virgin material, and hence cleaning properties would be altered or diminished. In metal cleaning applications, solvent wastes can be recycled, and the resulting waste used in fuel blending programs. Recycled solvents are rarely used in precision cleaning due to perceived impurities. On-site solvent recovery could be utilized and such programs can be cost-effective. Even companies that purchase small, inexpensive solvent reclamation equipment offset the costs of solvent disposal (UNEP, 1999).

Alternative Solvent Technologies

In addition to the emission reduction approaches that use improved equipment and cleaning practices, there are several not-in-kind (NIK) technology processes and solvent replacements that can be used to substitute for PFC and HFC-containing systems. Approaches that use aqueous and semi-aqueous processes are described in detail in Appendix 8.1.

Alternative Solvent Fluids

In electronics, metal, and some precision cleaning end uses, alternative organic solvents with lower GWPs are being manufactured and integrated into the industry. Some of these solvents, such as HFCs, HFEs, hydrocarbons, alcohols, volatile methyl siloxanes, brominated solvents, and non-ODS chlorinated solvents, can be used as alternatives to PFC/PFPEs, CFCs, and HCFCs. This solvent substitution can have a major impact on reducing emissions of high-GWP gases. HFC, PFC/PFPE, and HCFC use is very small in the metal and electronic cleaning end uses, and generally occurs only in cases where there are no possible alternatives. These solvents are primarily used for precision cleaning and carrier fluid applications as alternatives to CFC-113 and methyl chloroform (as described in Appendix 8.1).

8.4 Cost Analysis

Cost analyses were conducted for the following mitigation options: alternative solvents, NIK alternatives, and retrofit options. The most viable mitigation option to reduce emissions from the solvents sector is to adopt alternative solvents. All cost analyses were performed for four- and eight-percent discount rates, with a ten-year project lifetime. Financial assumptions and results specific to each emission reduction option are presented below. Exhibit 8.5 summarizes HFC and PFC/PFPE emission reductions by cost per metric ton of carbon equivalent (TCE).

Alternative Solvents

Adopting an alternative solvent is an approach that can be used to reduce the GWP-weighted emissions from the solvents sector. This option can be relatively inexpensive on a carbon basis given similar chemical prices and use rates for the available HFC and HFE solvents (Kenyon, 2000). For the purposes of this report, it was estimated that a significant portion of the PFC solvent market could be replaced by alternative solvents—25 to 50 percent—while five to 20 percent of the HFC solvent market could be replaced. Based on expert opinion, chemical prices are higher using alternative solvents, with increased costs ranging from \$0.20 to \$1.65 per kilogram of HFE or HFC. Of the available options, alternative solvents can have the largest impact on 2010 baseline emissions at the lowest cost (\$0.88/TCE). They represent a potential reduction of 0.8 MMTCE, over 30 percent of the baseline forecast.

NIK Replacements

Aqueous and semi-aqueous NIK replacement options can displace HFC, PFC, and HCFC usage in some solvent applications. For the purposes of this report, it was estimated that up to 10 percent of the HFC solvent use could be replaced with both aqueous and semi-aqueous NIK alternatives. For the cost analysis, it is assumed that the incremental investment required to convert a typical process may cost up to \$60,000 with annual operating savings between \$1,000 and \$2,000. Annual emissions avoided for a standard unit range from 300 to 1,000 kilograms/year (ICF Consulting, 1992). Together, NIK alternatives have the potential to reduce emissions from the solvents sector by about 3 percent of the 2010 baseline.

Retrofit Options

The costs of retrofitting solvent processes to reduce emissions could range from \$2,000 to over \$100,000. Given that solvent prices are relatively high, the analysis assumed that most solvent users will opt to invest in equipment options to minimize solvent losses in the baseline. In many cases, investments in retrofit options will be profitable for the end users. It was estimated that up to 10 percent of the HFC solvent market could be affected by implementation of emission reduction retrofit technology. For the cost analysis it was assumed that a \$20,000 investment might reduce annual emissions from a typical solvent process by up to 10 percent, for an annual reduction of 40 kilograms (Durkee, 1997). Retrofit options could reduce emissions at relatively low costs (\$42.45 and \$71.24 per TCE at four and eight percent discount rates, respectively) by 0.04 MMTCE in 2010, or two percent of baseline emissions.

Exhibit 8.5: Emission Reductions and Cost in 2010

Option	Break-even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate		MMTCE	Percent	MMTCE	Percent
	4%	8%				
Alternative Solvents	0.88	0.88	0.82	31%	0.82	31%
NIK Semi-Aqueous	9.63	11.55	0.03	1%	0.85	32%
NIK Aqueous	21.57	25.02	0.04	2%	0.89	34%
Retrofit Options	42.45	71.24	0.04	2%	0.93	35%

Notes:

2010 baseline emissions from the solvents sector equal 2.7 MMTCE.

Conversions to MMTCE are based on the GWPs listed in the Introduction to the report.

8.5 References

- Clement, Richard W., John H. Rains, Robert Simmons, and Kenneth Surprenant. Date Unavailable. *Solvent Cleaning*. The ASM Committee on Solvent Cleaning.
- Durkee, J.B. 1997. *Chlorinated Solvents NESHAP -- Results to Date, Recommendations and Conclusions*. International Conference on Ozone Layer Protection Technologies. November 12-13, 1997. Baltimore, MD.
- EPA. 2000. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1998*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC; EPA 236-R-00-001. (Available on the Internet at <http://www.epa.gov/globalwarming/publications/emissions/>).
- ICF Consulting. 1992. *Atmospheric and Related Health Effects of Alternatives to Class I Substitutes: Solvent Cleaning*. Prepared for Significant New Alternatives Program, Global Change Division, United States Environmental Protection Agency.
- Kenyon, William. 2000. Personal communication with ICF Consulting, Washington, DC, February 10, 2000.
- March Consulting Group. 1998. *Opportunities to Minimize Emissions of Hydrofluorocarbons (HFCs) from the European Union*. Final Report. Prepared by March Consulting Group, United Kingdom.
- March Consulting Group. 1999. *UK Emissions of HFCs, PFC, and SF₆ and Potential Emission Reduction Options*. Final Report. Prepared by March Consulting Group, United Kingdom.
- Olsen and Associates. 1999. (Available on the Internet at http://www.oanda.com/converter/cc_table).
- UNEP. 1999. *1998 Report of the Solvents, Coatings, and Adhesives Technical Options Committee (STOC): 1998 Assessment*. United Nations Environmental Programme, Ozone Secretariat.

Appendix 8.1: Solvents End Uses, Alternatives, and Technologies

End Uses and Cleaning Equipment

Electronics Cleaning

Electronics cleaning primarily involves the removal of resin flux from printed circuit boards (PCB) after soldering has been completed. Flux is a product that is applied to a PCB to enhance the quality of the solder joint by reducing the concentration of oxygen present at the time of soldering. While much of the flux is comprised of alcohols (volatilized during the soldering operation), many of the solids contained in the flux formulation remain on the PCB after soldering. CFC-113 and, to a lesser extent, methyl chloroform have traditionally been used as solvents in electronics cleaning to remove solids left behind after flux is incompletely volatilized. If not removed, these solids may cause performance-related problems and are visually unacceptable.

Precision Cleaning

Precision cleaning may apply to either electronic components or metal surfaces, but in either case is characterized by applications that require a high level of cleanliness in order to ensure satisfactory performance of the product being cleaned. Examples of products that might require precision cleaning include computer disk drives and navigational instruments. Both CFC-113 and methyl chloroform have been used to a similar extent in precision cleaning applications, CFC-113 because of its chemical stability and zero flammability, and methyl chloroform because of its high solvency and rapid evaporation rate.

Metal Cleaning

Metal cleaning is a process that removes a wide variety of contaminants from metal surfaces during manufacturing or maintenance services. At each stage in the manufacturing process, for example, contaminants must be removed from the piece to ensure a clean metal surface for the next step in the production process. The metal contaminants most often removed are greases and oils (used primarily as lubricants in the cutting and forming of metal pieces), particulate matter, and inorganic soils. In addition to primary metal and production cleaning, other metal changing operation uses for solvents include periodic maintenance of plant and equipment, and repair and service of equipment (UNEP, 1999). Most metal cleaning operations have used methyl chloroform because of its relatively low toxicity, high solvency power, low surface tension, and relatively low boiling point.

Solvent Cleaning Equipment

The three types of equipment typically used in solvent cleaning applications are cold cleaners, open top vapor degreasers, and conveyORIZED vapor degreasers.

Cold cleaners. These are most often tanks in which a contaminated piece is dipped into the cold solvent to remove particulate matter. These cleaners are fairly low in both capital and operating costs, because they have no heating units and require little if any energy consumption.

Open top vapor degreasers. These are the most widely used types of solvent cleaning equipment in the United States. They operate by heating the solvent in the bottom of the unit so that a vapor zone is created. The piece to be cleaned is lowered into the vapor zone and the solvent vapor acts to clean the contaminants from the piece. As the piece is raised out of the cleaner, the solvent is condensed back into a liquid and returns to the bottom of the unit.

Conveyorized vapor degreasers. These operate on the same principle as the open top units. However, they are designed for continuous operation and pieces to be cleaned are carried through the unit on a conveyor. This design allows for a greater throughput per cleaning machine and reduces the need for human interactions in the cleaning process.

Overview of Solvents and Cleaning Technologies

Solvents

HFCs and PFC/PFPEs are the primary high-GWP gases that are emitted from solvent use. Currently, the most popular alternative solvents are chlorinated solvents, HFEs, hydrocarbons, alcohol solvents, methyl siloxanes, and brominated solvents. HCFCs, HFCs, and PFCs are described in this analysis because of their continued use in various precision cleaning end uses.

Chlorinated Solvents. Chlorinated solvents are feasible alternatives to HFCs in precision cleaning. The process is similar to traditional solvent cleaning processes, with the exception of the solvent used. Non-ODS chlorinated solvents such as perchloroethylene, trichloroethylene, and methylene chloride can be used in traditional vapor degreasing equipment with additional engineering controls to limit emissions or in newly designed “tight” equipment that keeps emissions to a minimum.

HCFC Solvents. HCFCs are serving some limited and unique applications where other suitable alternatives have not been identified, including: cleaning delicate materials (such as cultural heritage and archival property); cleaning assemblies or components with sensitive materials or particular soils; cleaning certain oxygen systems; cleaning where explosive or flammable conditions are possible; and serving as a carrier of oil in precision cleaning applications. HCFCs are used in precision and electronic cleaning where compatibility of the solvent with the substrate to be cleaned is critical. The currently used HCFC in this application is HCFC-225ca/cb. All HCFCs, including HCFC-225, are subject to additional reductions in production and consumption with a phaseout in the United States by 2014.

HFC Solvents. In the mid-1990s, HFC-4310mee was introduced to replace CFC-113 in many applications. It has better solvent properties than PFCs and has more desirable environmental properties, such as zero ozone depletion potential and a very short atmospheric lifetime compared to PFCs and CFC-113. HFC-4310mee, both used alone and with additives such as alcohol, hydrochlorocarbons, and hydrocarbons in azeotropic proportions, was introduced to meet critical cleaning needs to replace CFC-113 in electronics defluxing, ionic impurities removal, and precision cleaning applications. HFC-4310mee has also replaced some uses of PFC and CFC-113 as a carrier fluid for lubricants applied to computer hard disks, in some precision bearing lubrication applications, for displacement drying of minute electronic and optical components, and as a flush fluid for removal of particulates in precision cleaning. The Police Scientific Development Branch of Scotland Yard has tested and qualified HFC-4310mee as an acceptable solvent alternative to CFC-113 for use in developing latent fingerprints from porous material, such as paper. Likewise, federal and some state forensic laboratories in the United States and authorities in Japan have also qualified HFC-4310mee for these uses and continue to make inroads into forensic uses of CFC solvents that are currently allowed under terms of the global laboratory and analytical essential use exemption. HFC-4310mee has also replaced CFC-113 as an essential part of a rain repellent formulation for aircraft windshields. Although HFC solvents are used in many applications, the total global use in solvents and coatings is very small and estimated to be less than 1,000 to 2,000 metric tons, which was less than one percent of global CFC-113 uses in 1989 (UNEP, 1999).

Perfluorocarbon Solvents. Perfluorocarbons (PFCs) such as C_5F_{12} , C_6F_{14} , C_7F_{16} , and C_8F_{18} , were introduced as substitutes for ODS in the early 1990s, and are also used in some applications in which ODS solvents were never used. Though they have been replaced by other substances (predominantly

HFEs) in many of the processes for which they have historically been used, PFCs were (and are still, to some degree) used as a carrier fluid for fluorolubricants in computer hard disk drives, as a flush fluid for particulate removal in precision cleaning, as a coolant in other electronic components, and as a rinsing agent in a co-solvent process for cleaning printed circuit boards and mechanical components containing oil, grease, and other soils. PFCs are being replaced in many applications by lower GWP HFEs and HFC-4310mee (UNEP, 1999).

HFE Solvents. Methyl perfluorobutyl ether is a mild solvent that can be blended with alcohols and other substances to increase solvency. It is a high cost solvent that is used for defluxing and/or degreasing high value parts and printed wiring assemblies (UNEP, 1999; March Consulting Group, 1998 and 1999). A family of fluorinated ethers (HFEs) was also developed during the mid-1990s as replacements for chlorinated and/or fluorinated solvents. Specifically, HFEs have successfully replaced PFCs, CFC-113, 1,1,1-trichloroethane, and HCFCs in certain precision cleaning operations, as well as in industrial aerosol solvent formulations. These HFEs and the various azeotropic formulations based on HFEs are the newest substitutes and are used in critical cleaning applications where compatibility with the substrate to be cleaned is essential. HFEs are also being utilized as replacements for some of the HCFC-141b and HCFC-225ca/cb solvent uses scheduled for phaseout. The advantages of HFEs are that they have no ozone depleting potential, have low toxicity, and are non-flammable. The GWPs of commercially available HFE-7100 and HFE-7200 are 390 and 55, respectively. HFC-4310mee has a GWP of 1,300, a factor of 4 to 30 times higher than these HFEs. However, HFEs will not always be substitutes for HFC-4310mee due to application specific requirements.

Hydrocarbon and Alcohol Solvents. Hydrocarbons are primarily used for metal and general cleaning requiring good solvency. Alcohols (i.e., isopropyl alcohol) and hydrocarbons are used for electronics and precision cleaning (UNEP, 1999; March Consulting Group, 1998 and 1999). Hydrocarbons vary in level of toxicity, and those with cyclic or aromatic molecular structure have a higher level of toxicity. The disadvantages of hydrocarbons and isopropyl alcohol include flammability risks and minor health hazards to handlers of these solvents (UNEP, 1999).

Volatile Methyl Siloxanes. The volatile methyl siloxanes are used as mild solvents suited primarily for cleaning silicone and other light, nonpolar residues. Since this is a high cost solvent, it is used for defluxing and/or degreasing high value parts and printed wiring assemblies. These solvents are also flammable and have low flash points. Therefore, these compounds are used in specialized equipment (UNEP, 1999).

Brominated Solvents. Some international manufacturers and suppliers are marketing two brominated solvents -- n-propyl bromide (nPB) and chlorobromomethane (CBM)—as replacements for HFC-4310mee, CFC-113, and the HCFCs (HCFC-141b and HCFC-225ca/cb). Both CBM and nPB are short-lived in the atmosphere and have small, positive, though uncertain, ODPs.

- **N-propyl bromide** is an aggressive solvent with a moderate boiling point that generally requires a stabilizer package and does not have a flash point (UNEP, 1999). This solvent has a low ODP and a low GWP. However, because nPB has a very short atmospheric lifetime of only 11 days, the ODP will depend on where it is emitted and the time of the year. It is compatible with metals, has a low tendency to cause corrosion, and can be used in most vapor degreasing equipment. The economic benefits of nPB are that it is easily recycled and moderately priced. The EPA, under the SNAP program, has not yet approved nPB as a substitute for ODS pending the availability of further ODP and toxicity data. However, its use in the rest of the world is rapidly increasing.
- **CBM** has unacceptably high toxicity, and the EPA has disapproved its use as a solvent in the U.S. under SNAP (UNEP, 1999).

Cleaning Technologies

CFC-113 and PFCs can be replaced in many applications with NIK alternatives by either modifying the process or cleaning requirements without compromising safety, performance, or compatibility. These NIK technologies are: (1) water-based cleaning and (2) no-clean processes, described below (UNEP, 1999).

Water-Based Cleaning. Water-based cleaning involves aqueous and semi-aqueous methods that have already been adopted widely in the metal and electronics cleaning sectors to replace CFC-113 and methyl chloroform. They can also be applied to many applications of HCFC-141b.

- **Aqueous cleaning** is a promising alternative process. The process uses a water-based cleaning solution that often contains a detergent to remove contaminants. The products are then rinsed with water. Aqueous processes have lower material costs than traditional solvent processes due to the low cost of water, but energy costs are comparable to and in some instances higher than CFC-113 and methyl chloroform processes. Depending on the level of contamination and local discharge regulations, wastewater treatment may be required before the water is discharged. However, in order to minimize wastewater discharge and the cost associated with wastewater discharge processes, “closed-loop” systems are available in which the water is separated out of the cleaning solution, treated, and reused (ICF Consulting, 1992).
- **Semi-aqueous cleaning**, or hydrocarbon-surfactant cleaning, is another alternative process that is likely to be widely used as a replacement in electronics, metal, and precision cleaning. A semi-aqueous process uses a cleaning solution, often a hydrocarbon/surfactant combination, to remove contaminants such as metal particulates, oil, and grease. The products are then rinsed with water. Semi-aqueous processes have lower material and energy costs than traditional solvent processes that use CFC-113 and methyl chloroform. Depending on the level of contamination and local discharge regulations, wastewater treatment may be required before the rinse water is released. As with aqueous cleaning, “closed loop” systems can be purchased that allow the re-use of water used in the cleaning process (ICF Consulting, 1992). Some of the benefits of using a semi-aqueous process are good cleaning ability, suppressed vapor pressure, non-alkalinity, reduced evaporative loss, potential decrease in solvent consumption, and ability of some formulas to separate easily from water. Some of the disadvantages of this process can include: flammability concerns that might require improved equipment design; many solvents used in the system are VOCs; and some applications may require high purity water, which is expensive (UNEP, 1999).

No-Clean Processes. No-clean processes refer to technologies that many manufacturers, especially in the electronics sector, have been able to implement without the need for traditional cleaning (March Consulting Group, 1998 and 1999). For example, “no-clean” soldering processes result in the elimination of cleaning and thus the need to use any solvent. There are two kinds of processes that could be implemented to switch a manufacturing line to a “no-clean” process, which are described below.

- **Use of low-solids flux or paste.** Low-solids fluxes serve the same purpose as their traditional counterparts, but leave significantly less residue on the PCB after soldering. They often contain two to five percent solids, as compared to 10 to 40 percent solids found in traditional fluxes. Many companies have tested low-solid fluxes in their production facilities and have determined that the small amount of residual flux remaining from the use of these formulations does not damage the quality of the board.
- **Soldering in a controlled atmosphere.** Controlled atmosphere soldering is identical to traditional wave and reflux soldering operations. The only difference is that the atmosphere is inerted by pumping nitrogen into the soldering chamber to remove oxygen and allow for a more efficient operation. Soldering in an inert atmosphere results in a significant reduction in the amount of flux and solder paste used due to the high efficiency of the process (ICF Consulting, 1992).

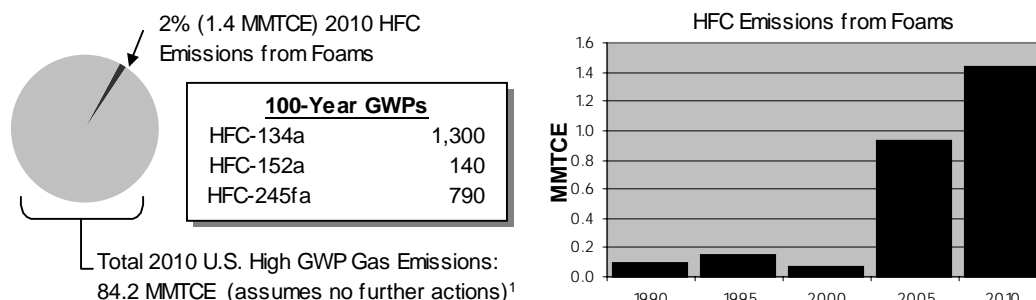
9. Cost and Emission Reduction Analysis of HFC Emissions from Foams in the United States

9.1 Introduction

Various hydrofluorocarbons (HFCs) are used as blowing agents during the manufacture of foams for many end uses. Two such HFCs that are currently available include HFC-134a and HFC-152a. Developmental quantities of HFC-245fa are available, with full-scale production scheduled for 2002. HFC-365mfc might also be used if and when commercialized. These blowing agents might be emitted to the atmosphere during the foam manufacturing process or on-site foam application, while foams are in use, and when foams are discarded. HFC-134a, HFC-152a, and HFC-245fa have 100-year GWPs of 1,300, 140, and 790 times the warming potential of carbon dioxide, respectively. By 2010, under a business-as-usual scenario, the United States could emit 1.4 MMTCE of these HFCs from foams and foam manufacture (See Exhibit 9.1).¹

Historically, chlorofluorocarbons (CFCs) were the primary blowing agents used in the foams industry before they were found to be ozone-depleting substances (ODS). Under the Montreal Protocol, the United States and 22 other nations agreed to phaseout CFCs and to use hydrochlorofluorocarbons (HCFCs) as interim substitutes. Section 610 of the Clean Air Act banned the sale and distribution of most foam products manufactured with HCFCs. “Essential uses” are exempt from this restriction on HCFC use as substitutes and include foam insulation products and foams used for motor vehicle safety that do not have adequate substitutes (EPA, 1993). The most commonly used blowing agents in these

Exhibit 9.1: U.S. Historical and Baseline HFC Emissions from Foams²



¹ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

² While CFCs and HCFCs are also greenhouse gases, IPCC Guidelines do not include reporting instructions for emissions of ozone depleting substances because they are being phased out under the Montreal Protocol. For purposes of this report, emissions of CFCs and other ODSs from the foam and other sectors are considered to be zero.

sectors were HCFC-141b, HCFC-142b, and HCFC-22. Upon implementation of the HCFC phaseout, which will eliminate import and production of HCFC-141b by 2003 and HCFC-22 and HCFC-142b by 2010, HFCs are expected to capture a larger share of the foam-blowing market. Other potential alternative blowing agents that are applicable in many end uses include hydrocarbons (HCs), water-blown or *in situ* CO₂ (CO₂/water), liquid CO₂ (LCD), and blends of the above.

There are two main types of foams: open cell and closed cell. Open cell foams experience significant blowing agent leakage due to the cell structure. However, because these foams are not typically produced with HFC blowing agents, HFC emissions from this sector are not significant. HFCs are often used in closed cell foam applications for their physical and performance properties. As these foams age, a certain amount of blowing agent may migrate out of the foam. The leakage rate is specific to each foam application, and varies according to the physical properties of the raw materials (e.g., solubility, polymer type, foam cell structure and type of processing) and to the extent that the foam is encapsulated (e.g., type of encasing material, combination of materials, etc.). HFCs can also be emitted at disposal, but a certain amount of blowing agent might remain in closed cell foams permanently.

9.2 Historical and Baseline HFC Emission Estimates

EPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes, including HFCs and PFCs (See Appendix A). The model tracks the use and emissions of various compounds for the annual “vintages” of new equipment (or products, such as foams) that enter service in each end use. Based largely on data available from industry sources and technical publications, the model estimates ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Fugitive emissions for each end use are estimated by applying annual leak rates and release profiles. The model accounts for ODS substitutes emitted during the manufacturing of foam and for

Exhibit 9.2: U.S. EPA's Vintaging Model Emissions Profile for the Foams Sector

Foams Sector	Loss at Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)	Loss at Disposal (%)	Total
Flexible PU	NA	NA	NA	NA	NA
Polyisocyanurate Boardstock	10	1.5	50	15	100
Rigid PU Integral Skin	95	2.5	2	0	100
Rigid PU Appliance	4	0.25	15	92.25	100
Rigid PU Commercial Refrigeration	6	0.25	15	90.25	NA
Rigid PU Spray	25	1.5	50	0	100
One Component	100	0	0	0	100
Rigid PU Slabstock and Other	37.5	0.75	15	51.25	100
Phenolic	25	1.125	32	39	100
Polyolefin	95	2.5	2	0	100
XPS Foam Sheet	NA	NA	NA	NA	NA
XPS Boardstock *	NA	NA	NA	NA	NA
Sandwich Panel	10	0.5	50	65	100

Source: EPA estimates.

Notes:

PU – Polyurethane

* This analysis assumes that XPS Boardstock will transition to a non-ODP/non-GWP substitute in 2010.

losses from the foam throughout its lifetime and at disposal (see Exhibit 9.2). By aggregating the data from various end uses, the model produces estimates of annual use and emissions of each compound.

There are several regulatory programs in place, e.g., the Significant New Alternatives Policy (SNAP) Program, to limit use of ODS substitutes in some applications. These programs are expected to result in significant reductions in ODS substitute emissions. These reductions are incorporated in the baseline estimate (see Exhibits 9.3 and 9.4). This cost analysis evaluates the cost of reducing emissions from this baseline.

Exhibit 9.3: Historical U.S. HFC Emissions from the Foam Sector (1990-1999)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	0.10	0.16	0.22	0.29	0.23	0.15	0.06	0.06	0.06	0.07

Source: EPA estimates.

Notes:

Note that emissions are not broken down by chemical to avoid disclosure of confidential business information.

Conversion to MMTCE is based on the 100-year GWPs listed in the Introduction to the report.

Exhibit 9.4: Baseline U.S. HFC Emissions Forecast for the Foam Sector (2000-2010)

	2000	2005	2010
Emissions (MMTCE)^{a,b}	0.07	0.93	1.43

Source: EPA estimates.

Notes:

Note that emissions are not broken down by chemical to avoid disclosure of confidential business information.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the report.

Forecast emissions are based on a business-as-usual scenario, assuming no further action.

EPA's historical emissions and hypothetical baseline forecast make certain assumptions about market penetration of CFC substitutes:

- HFC-134a was used in certain integral skin foam applications beginning in 1994 (as a result of the non-essential use ban of HCFC substances).
- HFC-152a was used in polyolefin foams beginning in 1994.

Because the HCFC phaseout will eliminate import and production of HCFC-141b by 2003 and HCFC-22 and HCFC-142b by 2010, HFCs are expected to become an important substitute foam-blowing agent in insulating foams, leading to the projected increases in HFC emissions in 2005 and 2010.

9.3 Applicability of Non-HFC Blowing Agents

The foam sector can be divided into three broad categories: thermoset foams, thermoplastic foams, and sandwich panels. Sandwich panels are produced with foams of both types, so this end use is addressed separately. The following section presents a market characterization and technical issues regarding the use of HFCs, and the potential applicability of using hydrocarbons, water-blown CO₂, and liquid CO₂ in the different foam market sectors.

Thermoset Foams

Thermoset foams are produced through a liquid manufacturing process, involving a reaction between a blend of two or three chemicals (e.g. “A”, “B”, and/or “C” sides). Initial conditions are typically room temperature and atmospheric pressure. The reaction increases the temperature of the mix and the viscosity of the reactants. The resultant material is essentially a solid with small gas filled cells throughout (DOW, 2000). Various foam end uses manufactured using this process are discussed below.

Polyurethane (PU) Flexible Foams

Foams from this end use are used in a variety of products, including furniture, bedding, automotive interiors, and carpet underlay. Because of the non-essential use ban under Section 610 of the Clean Air Act, these foams are no longer produced with CFCs or HCFCs. Commonly used ODS alternatives include water-blown CO₂, methylene chloride, acetone, pentane, liquid CO₂, extended-range polyols, additives, accelerated cooling, and variable pressure. HFCs are not expected to be used as blowing agents for this end use (UNEP, 1998). Therefore, this sector is not considered or discussed in this report.

PU Integral Skin Foams

Most integral skin foams are used in the automotive industry for seat cushions, back cushions, armrests, and headrests as well as for general purposes such as shoe soles, skis, and flotation devices. CFC-11 was used as the blowing agent in this application prior to the CFC phaseout. Section 610 of the Clean Air Act banned the sale and distribution of integral skin foam manufactured with HCFCs, so these foams are currently produced using non-ODP blowing agents such as HFC-134a, water-blown CO₂, and hydrocarbons. HFC-134a is primarily used in transportation applications such as armrests and steering wheels as well as shoe soles and flotation devices. HFC-245fa can also be used in this sector (UNEP, 1998; Honeywell, 2000a,b).

Substitute HFC technologies available for flexible integral skin include water-blown CO₂ formulations, which require additional in-mold coatings (IMC) to be injected for some applications, and n-pentane blown foams where very durable skin is required. However, these options might not be as effective in warmer climates due to poorer solubility in polyols. For other sectors such as flexible integral skin shoe soles, water-blown CO₂ is a technically feasible and economically viable option. For rigid integral skin foams, water-blown CO₂ and n-pentane are both technically feasible options (UNEP, 1998).

PU Rigid Foams

PU insulating foams include polyurethane and polyisocyanurate laminate boardstock, appliance, spray, sandwich panels, slabstock, and other foam products. CFC-11, and to a lesser extent CFC-12, were used as the major blowing agents in these applications. HCFC-141b has been the primary replacement for CFCs in polyurethane insulating foams because of similar insulation performance and low capital investment. HCFC-142b, HCFC-22, and blends of the two have also taken a small share of that market. Upon implementation of the HCFC phaseout, these compounds will likely be replaced by non-ODP alternatives such as hydrocarbons, HFCs, and CO₂. Some manufacturers of polyurethane insulating foams (e.g., polyisocyanurate boardstock) have already begun the transition out of HCFCs (UNEP, 1998).

Non-HFC blowing agents applicable to specific end uses in this sector are discussed below.

- **Rigid Polyurethane and Polyisocyanurate Laminated Boardstock.** The primary application for these products is insulation in buildings. Historically, this sector used CFC-11 and then transitioned into HCFC-141b and small amounts of HCFC-141b/22 blends. Viable non-ODP alternatives include hydrocarbons, HFC-245fa, HFC-245fa co-blowing with CO₂/water (HFC-245fa/CO₂), HFC-365mfc, as well as blends of the above (UNEP, 1998; Honeywell, 2000a,b; Alliance, 2001).

Non-HFC options for this sector include hydrocarbons and hydrocarbon blends. Hydrocarbons are being used by at least two U.S. manufacturers (UNEP, 1998; Honeywell, 2000a,b).

- **Rigid PU Appliance and Commercial Refrigeration Foams.** These foams are used in domestic and commercial refrigerators and freezers. CFC-11 was the primary blowing agent used in this sector prior to the CFC phaseout. Currently, the majority of appliance manufacturers use HCFC-141b as a blowing agent, although small amounts of HCFC-142b, HCFC-22, and HFC-134a might be used. HFC-245fa, HFC-134a, and hydrocarbons are all potential non-ODP alternatives. These blowing agents might also be used with small amounts of *in situ* CO₂ (UNEP, 1998; Honeywell, 2000a,b; Alliance, 2001).

The U.S. appliance industry continues to face significant barriers associated with hydrocarbons, such as significant VOC and flammability concerns, as well as energy penalties. *In situ* CO₂ might also be a potential option if: 1) it is used in conjunction with alternative insulation technologies such as vacuum panels (assuming cost and performance issues are solved) and 2) both the external and internal skins are metal, to significantly retard/eliminate diffusion issues (UNEP, 1998; Alliance, 2001).

- **Rigid Spray PU Foam Insulation.** Spray foam (SPF) is primarily used for *in situ* applications of roofing, rigid thermal insulation, and air barriers, usually in residential and commercial buildings, industrial storage tanks, piping and ductwork, and refrigerated transport trailer and tanks. These foams are produced in the field from a hand-held spray gun. Currently, the main blowing agents used in this industry are HCFC-141b and *in situ* CO₂. Potential non-ODP alternatives in this sector include HFC-245fa, HFC-245fa/CO₂, CO₂/water, HFC-365mfc, and hydrocarbons, as well as blends with CO₂ and water (UNEP, 1998; Honeywell, 2000a,b; Alliance, 2001).

In situ CO₂ and hydrocarbons are potential non-HFC blowing agents for this end use. However, key technical issues that need to be addressed for both alternatives include poorer fire performance, dimensional stability, and thermal performance. Despite the significant uncertainties about the details of the transition from HCFC-141b in this sector, EPA believes that for this analysis it is reasonable to assume a range of plausible transition scenarios. EPA plans to work closely with industry to gather additional information as it becomes available to refine this analysis.

In situ CO₂ formulas have a much lower insulation value than HFC formulas, and lower closed cell content. On the processing side, limitations on the minimum ambient processing temperature may act as a considerable constraint in many areas of the United States. While there are some test applications being monitored on roofing applications, it is too early to determine if the foams produced from this technology will perform adequately. In addition, building codes and standards and industry guidelines would have to be changed to allow the use of *in situ* CO₂ blown SPF.

Hydrocarbon blown foams also have challenges that will be more difficult to overcome. The SPF industry is very concerned about the safety of using hydrocarbon blown SPF in field applications. EPA SNAP approval of hydrocarbon blown foam requires the applicator to complete extensive safety training and certification and is limited to only Exxol blowing agents. At this time, an adequate safety program that complies with this requirement has yet to be implemented on a large scale (UNEP, 1998; Honeywell, 2000a,b; Alliance, 2001).

- **Rigid Polyurethane Slabstock.** Slabstock, also known as bunstock, can be fabricated into different shapes and forms, and is used as thermal insulation for a variety of applications including pipes, storage tanks, construction, and refrigerated transport containers. The industry

switched from CFC-11 to HCFC-141b, although there is some use of pentane and water-generated CO₂. Zero-ODP blowing agent alternatives include HFC-245fa, hydrocarbons, *in situ* CO₂ and blends of the above (UNEP, 1998; Honeywell, 2000a,b; Alliance, 2001).

One-Component Foams (OCF)

These foams are used in a variety of building applications such as draft-proofing, sealing door and window frames, and joining insulating panels, roofing boards, and pipe-insulation. Because OCF foams come in pressurized canisters and cylinders, they are also called aerosol foams. OCF blowing agents are typically gaseous, as they function as both a blowing agent and a propellant for the foam. Historically, this sector has primarily used CFC-12, but transitioned into HCFC-142b, HCFC-22, HCFC-142b/22 blends, HFC-134a, HFC-152a, and hydrocarbon blends after the CFC phaseout. Non-ODP options include hydrocarbons, HFC-134a, HFC-152a, HFC-365mfc, and blends of these compounds with HFC-245fa (Honeywell, 2000c,d; UNEP, 1998; Alliance, 2001). Hydrocarbons are currently used for most OCF production (UNEP, 1998; Honeywell, 2000b).

Phenolic Foams

These foams have excellent fire retardant and thermal insulation properties, and have been used in commercial building applications. However, little, if any, phenolic foam is being produced in the United States (EPA, 1993; UNEP, 1998). Consequently, this end use is not considered or discussed in this report.

Thermoplastic Foams

Unlike thermoset foams, thermoplastic foams are not manufactured via chemical reactions. Instead, a plastic resin is melted under high temperature and pressure. As the pressure is released, the blowing agent expands, causing the material to expand. The foaming material is then forced through a small die opening, resulting in a continuous board of desired thickness. When exposed to sufficient heat, thermoplastic foams can melt and return to its polymeric molten state (DOW, 2000). Foams manufactured using this process include polyolefin, expanded polystyrene (EPS), extruded polystyrene (XPS) sheet, and XPS boardstock applications. These end uses and non-HFC blowing agents applicable to this sector are discussed below.

Polyolefin Foams

Polyolefin foams include products made from polyethylene and polypropylene resins. The most common applications for these foams include pipe-wrap insulation, construction materials, protective packaging, flotation devices, and automotive bumper systems. Historically, this sector used CFC-114 and CFC-12, but transitioned into HFC-152a after the CFC phaseout. Most non-insulating applications have now switched to isobutane, but HCFC-142b and HCFC-142b/22 blends are still being used in the production of pipe-wrap insulation. Some manufacturers might also be using HFC-134a and HFC-152a. Non-ODP alternatives include HFC-134a, HFC-152a, hydrocarbons, and LCD (UNEP, 1998; Honeywell, 2000b; Alliance, 2001).

XPS Sheet

These foams are used in a variety of applications including food service and food packaging products such as single-service plates, cups, and egg cartons, and protective packaging for furniture and electronic devices. For these applications, a thermoforming manufacturing process is used. Other applications included laminated sheets, which are typically used in insulating sheathing applications. Historically, foams were primarily produced with CFC-12 as a blowing agent. Following the CFC phaseout, the vast

majority of U.S. XPS sheet thermoforming manufacturers transitioned directly into hydrocarbons. Some amount of HFC-152a is used in regions where VOCs are a concern (UNEP, 1998; Alliance, 2001).

XPS Boardstock

These foams are used for insulation purposes for roofs, floors, walls, tile and plaster backing applications, as well as being core material for sandwich panel construction and a small number of specialty applications. HCFC-142b and a blend of HCFC-22/HCFC-142b are the most common replacements for CFCs in insulating XPS boardstock. In anticipation of the 2010 phaseout date for HCFC-142b and HCFC-22, the XPS industry is researching alternatives to HCFCs. This research includes HFCs and hydrocarbons, blends of these alternatives with water-blown CO₂, and LCD (DOW, 2000; FPSA, 2000; Honeywell, 2000b; UNEP, 1998).

Several European manufacturers have begun to implement non-HCFC alternatives. However, options that are viable in Europe might not be directly applicable to the United States because the markets differ: the Europeans value strength and compressibility, while the U.S. market places a premium on insulating properties and low density (FPSA, 2000). U.S. manufacturers hope to continue to use HCFC-142b and HCFC-22 until the 2010 phaseout date (DOW, 2000). Given the length of time before this phaseout and the related uncertainties in the U.S. transition, no assumptions will be made at this point on what specific alternatives will ultimately be implemented in the United States for XPS boardstock. Thus, this leads to a default assumption that whatever alternatives are implemented will not have any greenhouse gas emissions; the Agency recognizes that more accurate projections will be possible as the 2010 phaseout date approaches.

EPS Foam

EPS boards and sheets are distinguished by its associated manufacturing process, typically steam molding. EPS products historically did not use CFCs as the blowing agent. Thus, any calculations regarding HFC emission contributions or reductions from sheet applications will be limited to XPS sheathing insulation products for the purposes of this chapter (Alliance, 2001).

Sandwich panels

This end use is so named because it consists of foam cores between rigid facings. These foams are valued for their insulating and self-adhesive qualities, and are used in various applications including doors, panels, water heaters, cold storage, and in the transport industry for insulated trucks and reefers. Historically, CFC-11 was the primary blowing agent used in this application. Today, the industry is mainly using HCFC-141b, although HCFC-22, HCFC-142b, HFC-134a, water-blown CO₂, hydrocarbons, and blends of the above are being used by specific end uses. Following the HCFC phaseout, the likely blowing agents include HFC-245fa, HFC-134a, HFC-152a, CO₂/water, LCD, and blends of the above (UNEP, 1998; Honeywell, 2000a,b).

Water-blown CO₂, hydrocarbons, and LCD are all potential non-HFC alternatives in this sector (UNEP, 1998; Honeywell, 2000a,b). Because this end use is comprised of thermoset and thermoplastic foams, the choice of blowing agent substitute depends on the specific application. In polyurethane and XPS foam insulating applications, the use of non-HFC blowing agents might result in poorer thermal performance, necessitating an increase in foam thickness to achieve comparable R-values. Thus, using non-HFC substitutes might create space constraints in areas such as refrigerated transport and walk-in-coolers for cold storage. Other key technical issues that need to be addressed in order to remain effective in sandwich panel applications include fire performance and dimensional stability (Alliance, 2001).

The applicability of hydrocarbons, LCD, and *in situ* CO₂ to various foam end uses are summarized in Exhibit 9.5.

Exhibit 9.5: Potential Applicability of Non-HFC Blowing Agents to Various End uses in the Foams Sector

End use	HFCs	LCD	<i>In situ</i> CO ₂	Source
Flexible Polyurethane	✓	✓	✓	UNEP (1998)
Polyisocyanurate Boardstock	✓			UNEP (1998)
Rigid PU Integral Skin	✓	✓		UNEP (1998)
Rigid PU Appliance	✓		✓	UNEP (1998), Alliance (2001)
Rigid PU Commercial Refrigeration	✓		✓	UNEP (1998)
Rigid PU Spray	✓		✓	UNEP (1998), Industry Communications
One Component	✓			UNEP (1998)
Rigid PU Slabstock	✓			UNEP (1998)
Phenolic	✓			UNEP (1998)
Polyolefin	✓	✓		UNEP (1998)
XPS Foam Sheet	✓	✓		UNEP (1998)
XPS Boardstock	✓	✓		UNEP (1998), Honeywell (2001a)
Sandwich Panel	✓	✓	✓	UNEP (1998), Honeywell (2001a)

Notes:

Only end uses which are currently using HFCs are listed.

"Industry Communications" are based on communications with multiple chemical producers, equipment manufacturers, and trade associations.

9.4 Cost Analysis

This section presents a cost analysis of achieving HFC emissions reductions from the 2010 baseline presented in Exhibit 9.4. A discounted cash-flow analysis was conducted to estimate break-even carbon prices in dollars per metric ton of carbon equivalent (TCE) associated with each blowing agent substitution. The model determined the net present value for each non-HFC alternative from an annual stream of cash flows, based on a start-up capital cost, annual variable costs, annual indirect costs, and annual revenue obtained from sales of emission reduction credits.³ The price of carbon was the unknown factor in determining revenue. The model solved for the value of carbon that would make the net present value of this cash flow equal to zero (i.e., the break-even carbon price). The analysis assumed a project lifetime of 25 years and was performed at discount rates of four and eight percent.

Emissions were addressed using a Life Cycle Climate Performance (LCCP) approach, which accounts for the following:

- HFC emission reductions from blowing-agent substitution,
- indirect emissions of CO₂ associated with energy efficiency differences resulting from the substitution (unless otherwise stated), and
- embodied energy and fugitive emissions from the manufacture of the HFC.⁴

Costs were based on the incremental differences between using the HFC and switching to the non-HFC. Financial information considered in the analysis include:

³ Emission reduction credits were HFC emission reductions achieved by the blowing agent substitution offset by indirect emissions due to energy efficiency discrepancies.

⁴ Embodied energy and fugitive emissions from the manufacture of the HFC are accounted for by adjusting the 100-year GWP used in the analysis, per the methodology described in Appendix A of Dieckmann and Magid (1999).

- capital costs, which account for equipment costs to modify existing plants and to maintain production capacity,
- blowing agent costs, which address the difference between costs and the quantity of the HFC and non-HFC alternative required,
- foam costs, which address changes in foam density, the amount of fire retardant used, the quantity and type of polyol, etc.,
- testing, training or other costs associated with transitioning to non-HFC alternatives, and
- indirect costs from energy efficiency differences (unless otherwise stated).

Conversion or “learning curve” costs, which consider short-term costs incurred due to yield, rate, and density penalties associated with conversion uncertainties as well as technical support costs, could not be addressed in the analysis because this type of information was not readily-available.

Reliable financial information is available for only two end uses: 1) PU spray foams and 2) PU appliance foams. Thus, only the results of the cost analysis for these applications and a summary are presented below.

PU Spray Foams

This analysis was based on a hypothetical spray foam contractor who produces approximately 127,000 pounds of foam using a 50/50 blend of HFC-245fa and CO₂ (water) as a blowing agent. The blowing agent constitutes approximately 10 percent of the foam, by weight. Various “base case” inputs and assumptions are presented in Exhibit 9.6. This cost analysis estimates the break-even carbon price for this hypothetical contractor to replace HFC-245fa/CO₂ (water) with two non-HFC blowing agents: 1) CO₂ (water) and 2) hydrocarbons. The foams manufactured with the two alternatives are assumed to compensate for lower insulating performance relative to HFC-blown foams by increasing the thickness and density of the foam. Thus, incremental differences in indirect emissions and costs associated with energy penalties are negligible.

Exhibit 9.6: Base Case Assumptions for a Hypothetical Spray Foam Contractor Using HFC-245fa/CO₂ (water)

Variable	Unit	Value	Source
Foam Produced	Lbs	127,000	Calculated
Blowing Agent Component of Foam	%	10	Industry Communication
Blowing Agent Consumption	Lbs	12,700	Estimated from Caleb (2001)
Foam Cost	\$/lbs	Approximately \$1 *	Assumption
Price of Isocyanate	\$/lb	1.00	Industry Communication
Price of HFC-245fa	\$/lb	4.00	Caleb (2001)

Notes:

* Approximate value based on available foam costs for appliances and water heaters.

“Industry Communications” are based on communications with multiple chemical producers, equipment manufacturers, and trade associations.

Cost factors that are addressed include:

- fire testing costs incurred by system houses for various formulations;
- capital equipment costs;
- employee training costs (hydrocarbons only);
- increased cost of foam components (e.g., polyols, additives, etc.);

- increased consumption of foam components to compensate for increased foam density;
- increased use of fire retardant; and
- incremental differences in the costs of blowing agents and the quantity required.

Annual emission reductions were determined based on the estimated amount of blowing-agent consumed by the hypothetical contractor and from the blowing-agent release profile used in the Vintaging Model (Exhibit 9.2).

Assumptions, the break-even carbon price, and the potential emission reductions in 2010 specific to each blowing agent substitution are presented below.

Replacing HFC-245fa/CO₂ (water) with CO₂ (water)

Assumptions specific to this substitution are presented in Exhibit 9.7. To be cost-effective, replacing HFC-134a with cyclopentane would require a carbon price of approximately \$114/TCE and \$123/TCE, at discount rates of four and eight percent, respectively. This substitution can potentially reduce about 0.5 MMTCE in 2010, or approximately 35 percent of baseline emissions from the foams sector.

Replacing HFC-245fa/CO₂ (water) with Hydrocarbons

Assumptions specific to this substitution are presented in Exhibit 9.8. An additional cost factored into the analysis for this alternative was the additional cost of training workers in handling, storing, and using hydrocarbons. Based on the assumptions made, it is estimated that replacing HFC-245fa/CO₂(water) with hydrocarbons would require a carbon price of approximately \$-16/TCE at both discount rates of four and eight percent. This substitution can potentially reduce about 0.5 MMTCE in 2010, or approximately 35 percent of baseline emissions from the foams sector. The Agency recognizes that this option may not be implemented because of safety and liability concerns.

Exhibit 9.7: Assumptions and costs used in the cost analysis to substitute HFC-245fa/CO₂ (water) with CO₂ (water)

Variable	Unit	Value	Source
Capital Costs	\$	Negligible ^a	Industry Communication
Fire Testing Costs	\$/Contractor	4,000 ^b	Caleb (2001), Industry Communication
Increased Fire Retardant Use	%	1	Assumption
Cost of Fire Retardant	\$/lb	2.00	Industry Communication
Price of Isocyanate	\$/lb	1.00	Industry Communication
Blowing Agent Component of Foam	%	6	Industry Communication
Increase in Foam Density	%	30 ^c	Industry Communication
Assumed Increase in Cost of Foam	\$/lbs	0.10	Assumption

Notes:

^a Assumes that contractors that are using HFC-245fa/CO₂ (water) have equipment that can use CO₂ (water) with minimal modification.

^b Based on \$250,000 per systems house, 20 systems houses, and approximately 1,250 spray foam contractors (Caleb, 2001; Industry Communication).

^c Assumes that foam density increases from 2.5 lb/ft³ to 3.25 lb/ft³.

"Industry Communications" are based on communications with multiple chemical producers, equipment manufacturers, and trade associations.

Exhibit 9.8: Assumptions and costs used in the cost analysis to substitute HFC-245fa/CO₂(water) with Hydrocarbons

Variable	Unit	Value	Source
Capital Costs	\$	10,000 ^a	Industry Communication
Fire Testing Costs	\$/Contractor	4,000 ^b	Caleb (2001), Industry Communication
Increased Fire Retardant Use	%	3	Assumption
Cost of Fire Retardant	\$/lb	2.00	Industry Communication
Price of Cyclopentane	\$/lb	0.90	Industry Communication
Blowing Agent Component of Foam	%	9	Industry Communication
Increase in Foam Density	%	20 ^c	Industry Communication
Assumed Increase in Cost of Foam	\$/lbs	0.10	Assumption
Employee Training Costs	\$/yr	\$6400 ^d	Industry Communication

Notes:

^a Assumes that technical issues can be resolved.

^b Based on \$250,000 per systems house, 20 systems houses, and approximately 1,250 spray foam contractors (Caleb, 2001; Industry Communication).

^c Assumes that foam density increases from 2.5 lb/ft³ to 3.0 lb/ft³.

^d Assumes a cost of approximately \$215/employee/day, 2 crews of 3 employees (total of 6 employees), and 5 days of training.

"Industry Communications" are based on communications with multiple chemical producers, equipment manufacturers, and trade associations.

PU Appliance Foams

Two blowing agent substitution options were considered for this end use:

- replacing HFC-134a with cyclopentane; and
- replacing HFC-245fa with cyclopentane.

This cost analysis was based on a hypothetical facility that manufactured approximately 540,000 refrigerators and consumed about 3.4 million pounds of blowing agent annually. The blowing agent was assumed to constitute approximately 12 percent of the foam. The costs of producing a refrigerator using each blowing-agent (e.g., HFC-134a, HFC-245fa, and cyclopentane) were provided by the refrigeration industry. Factors considered in these data include:

- capital costs to convert;
- blowing agent costs;
- foam costs (including density considerations);
- liner costs; and
- additional costs required to meet the 2001 National Appliance Energy Conservation Act (NAECA) energy efficiency standards.

Data have been aggregated to protect confidential information.

HFC emission reductions over time were derived from the blowing agent release profile used in the Vintaging Model (Exhibit 9.2), which accounts for release during manufacturing, annual leakage, and at disposal. Because the cost data assumes that the refrigerators manufactured using various blowing agents meet the same energy efficiency standards, incremental differences in indirect emissions and costs between the blowing agents are assumed to be negligible.

Replacing HFC-134a with Cyclopentane

To be cost-effective, replacing HFC-134a with cyclopentane would require a carbon price of approximately \$17/TCE and \$43/TCE, at discount rates of four and eight percent, respectively. This

substitution can potentially reduce about 0.03 MMTCE in 2010, or approximately two percent of baseline emissions from the foams sector.

Replacing HFC-245fa with Cyclopentane

To be cost-effective, replacing HFC-245fa with cyclopentane would require a carbon price of approximately \$229/TCE and \$341/TCE, at discount rates of four and eight percent, respectively. This substitution can potentially reduce about 0.19 MMTCE in 2010, or approximately 13 percent of baseline emissions from the foams sector. Because this analysis only addresses substitutions with break-even costs below \$200/TCE, this alternative is not listed in Exhibit 9.9.

Summary

Overall, assuming these hypothetical transitions to non-HFC alternatives are implemented, HFC reductions would total 1.03 MMTCE, or 72 percent of 2010 baseline estimates from the foams sector. Exhibit 9.9 summarizes HFC emission reductions by cost per metric ton of carbon equivalent for the year 2010 at discount rates of four and eight percent.

Exhibit 9.9 Emission Reductions and Costs in 2010						
Option	Break-even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate					
	4%	8%	MMTCE	Percent	MMTCE	Percent
PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with hydrocarbons	(15.70)	(15.64)	0.5	35%	0.5	35%
PU Appliance Foams - Replace HFC-134a with cyclopentane	17.18	43.25	0.03	2%	0.53	37%
PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with CO ₂ (water)	114.09	123.52	0.5	35%	1.03	72%
Notes:						
2010 baseline emissions from the foam blowing sector equal 1.43 MMTCE.						
Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.						
Sums might not add to total due to rounding.						

9.5 References

Alliance. 2000. *Comments of the Alliance for Responsible Atmospheric Policy on Draft of "Cost and Emission Reduction Analysis of HFC Emissions from Foams in the United States."* Fax sent May 26, 2000.

Alliance. 2001. *Review of EPA Draft Chapter 9 by Members of the Alliance for Responsible Atmospheric Policy.* May 16, 2001.

Caleb. 2001. *Overall Review of the Challenges Facing the Polyurethane Spray Foam Industry and Other Systems House Based Applications in the Light of Proposed Rulemaking [65 Fed. Reg. 42543, July 11th 2000].* Caleb Management Services Limited, UK.

Dieckmann, J., and H. Magid. 1999. *Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications.* Final Report to the Alliance for Responsible Atmospheric Policy. Arthur D. Little, Inc., Cambridge, MA; Reference Number 49648.

DOW. 2000. *Comments of the DOW Chemical Company Regarding EPA's Proposal to Accelerate the Phase Out of Certain Substitutes For Ozone Depleting Substitutes Under the Significant New Alternative Policy*. Personal Communication from Stephen Kris and Peter Wright of DOW to Anhar Karimjee of EPA on September 8, 2000. Available from EPA Foams Docket A-2000-18, Document IV-D-10.

EPA. 1993. *Background Document on Foam Products Made with Class II Substances*. Office of Air and Radiation, Stratospheric Protection Division.

FPSA. 2000. *Comments of the Foamed Polystyrene Alliance Regarding EPA's Proposal to Accelerate the Phase Out of Certain Substitutes For Ozone Depleting Substitutes Under the Significant New Alternative Policy*. Available from EPA Foams Docket A-2000-18, Document IV-D-25.

Honeywell, 2000a. *Comments of Honeywell Inc. on U.S. Environmental Protection Agency Proposed Listing of Certain HCFCs and Blends as "Unacceptable" Substitutes for HCFC-141b - 65 Fed. Reg. 42653 (July 11, 2000)*. Personal Communication from Richard Ayres of Howrey, Simon, Arnold, and White to Anhar Karimjee of EPA on September 11, 2000. Available from EPA's Foams Docket A-200-18, Document IV-D-41.

Honeywell, 2000b. Meeting Notes From Meeting Between Honeywell, Inc. and U.S. EPA on December 11, 2000. Available from EPA Foams Docket A-2000-18, Document IV-E-6.

March Consulting Group. 1998. *Opportunities to Minimize Emissions of Hydrofluorocarbons (HFCs) from the European Union*. Final Report. Prepared by March Consulting Group, United Kingdom.

Tao, W.H., W.F. Sung, and J.Y. Lin. 1996. *Development of Vacuum Insulation Panel Systems*. Polyurethanes EXPO '96. Pp. 43-47.

UNEP. 1998. 1998 Report of the Flexible and Rigid Foams Technical Options Committee. United Nations Environment Programme.

Williams, D.J., M.C. Bogdan, and P.B. Logsdon. 1999. Optimizing Performance and Value: HFC-245fa and Blends of HFC-245fa for Insulating Foams. Conference Proceedings from the Earth Technologies Forum TF 1999, pg 290-302.

Appendix 9.1: Description of HFC Emission Reduction Technologies and Practices

Opportunities to reduce HFC emissions from foams fall into the following categories: non-HFC blowing agents, use of lower GWP HFCs, alternative insulation technologies, and direct emission reduction. These options are discussed below.

Non-HFC Blowing Agents

The following section summarizes potential non-HFC blowing agents for various foam end uses. Three options are discussed below: hydrocarbons, water-blown CO₂, and liquid CO₂.

Hydrocarbons (HC)

Hydrocarbons such as propane, butane, isobutane, n-pentane, isopentane, cyclopentane, and isomers of hexane are SNAP-approved alternatives to HFCs. HCs are inexpensive and have lower GWP impacts relative to HFCs. However, key technical issues associated with hydrocarbons are:

- **Flammability.** HCs require stringent safety precautions in manufacturing, storage, handling, transport, and customer use, which necessitate factory upgrades and employee training. Specialized equipment that might be needed includes a dedicated storage tank for the hydrocarbon, pre-mixers, adapted high-pressure dispensers, suitable molds plus process exhaust, hydrocarbon detectors, and appropriate classification of electrical equipment. In order to reduce fire risks, some applications might also require the use of a larger quantity of flame-retardants and/or the use of a more expensive fire-retardant.
- **Volatile Organic Compounds (VOCs).** Because HCs contribute to ground level ozone and smog, they are highly regulated by the government. In many parts of the United States, HCs cannot be used without emission controls, which can significantly increase the costs of conversion.
- **Performance.** Some HCs only yield approximately 85 percent of the insulating value of HCFC-141b and HFC-245fa. Producing a thicker foam can compensate for this energy efficiency difference, but will increase the cost of production. This option might not be viable in fixed thickness applications such as appliances, or in applications where R-value is proscribed by code such as in PU spray roofing insulation. Other performance considerations include dimensional stability and solubility. Addressing these factors might require a more expensive and more limited polyol formulation.

Costs of converting to hydrocarbons and addressing technical considerations can be significant, but vary according to factory-specific needs. In spite of these issues, hydrocarbons are being considered in a wide variety of applications (UNEP, 1998; Alliance, 2000; Alliance, 2001;).

Liquid Carbon Dioxide (LCD)

The basic principle by which LCD blowing agents operate is expansion of liquid CO₂ to the gaseous state. Liquid CO₂ is blended with other foam components under pressure prior to the initiation of the chemical reaction. When decompressed, the CO₂ expands, resulting in the froth foam, which further expands with the additional release from the water/isocyanate reaction. LCD might require formulation changes to more readily dissolve the CO₂ and to prevent deactivation of PU catalysts. When LCD is introduced at the head, often referred to as third stream, the metering equipment can be quite complicated and, to date, unreliable. Difficulties encountered in using LCD include the limited solubility of the

chemical mixture, controlled decompression, and distribution of the unavoidable froth (UNEP, 1998). Foams blown with CO₂ might suffer from lower thermal conductivity, lower dimensional stability, and higher density versus HCFC blown foams. To overcome these limitations, CO₂ can be blended with hydrocarbons or HFCs (Williams *et al.*, 1999; Honeywell, 2000a; Alliance, 2001).

Water-Blown (*in situ*) Carbon Dioxide (CO₂/water)

In this process, CO₂ produced from a chemical reaction between water and polymeric isocyanate is used as a blowing agent. During manufacturing, no ODP or high GWP gases are emitted, and there are limited health and safety risks during processing. However, foams produced using CO₂/water are subject to the same performance limitations discussed for LCD-blown foams: lower thermal conductivity, lower dimensional stability, and higher density versus HCFC- and HFC- blown foams. LCD and CO₂ are generated *in situ*. In some PU foam applications, a major concern associated with using water-generated or LCD systems is the increased percentage of open cell content, which results in poorer water-proofing performance in water-proofing quality of the final product. Another consideration is that the polymeric isocyanurate content must be increased, which cannot be accommodated by some spray foam equipment. To overcome these limitations, CO₂ can be blended with hydrocarbons or HFCs (Williams *et al.*, 1999; Honeywell, 2000a; Alliance, 2001).

Although LCD and CO₂ generated *in situ* have similar performance issues, the process limitations associated with each differ. Less mechanical modifications are required to use *in situ* CO₂, and the foam manufacturer or spray foam applicator can be more certain of the final CO₂ content, and overall foam properties, than for LCD (Alliance, 2001).

Lower-GWP HFC Substitution

Manufactures can reduce their emissions on a carbon basis by switching from a blowing agent with a high GWP to one with a lower GWP, but any associated energy penalties must also be considered. Because choices of blowing agents are driven by performance and economic considerations (factors such as utility, functionality, solubility, vapor pressure tolerance, and cost) rather than GWP, options will vary depending on the type of foam (i.e., thermoset or thermoplastic), the manufacturing process, and the specific end use application.

Currently, HFC-134a is the most common HFC used in the foam industry and has a GWP of 1,300. HFC-245fa has a GWP of 790, and is expected to be commercially available in the United States by mid-2002. It has been identified as an effective substitute for many applications, including rigid and integral skin polyurethane. Initial industry reports indicate that HFC-245fa-blown foams have properties much improved over HFC-134a foams, and, for many applications, are comparable to those using CFCs or HCFCs (Honeywell, 2000a). Companies can potentially produce higher quality foams and reduce emissions on a carbon equivalent basis by substituting HFC-134a with HFC-245fa.

Due to lack of cost information, this HFC reduction option is not discussed further.

Alternative Insulation Materials and Technologies

Alternative insulation technologies in certain construction applications include fiberboard, fiber glass, and cellular glass. However, users often still select fluorocarbon foams because of superior properties such as fire resistance, structural rigidity, moisture resistance, and insulation effectiveness, even though they may be more expensive (March Consulting Group, 1998).

Vacuum panels have insulating capabilities significantly better than any foam insulation available today, and offer tremendous potential for the refrigeration industry. They are typically open-celled polyurethane or polystyrene foam encapsulated in a gas barrier. This assembly is then evacuated to give the panel its insulating properties. Implementation of this technology has been limited due to its high

costs. Any future use of vacuum panels in the United States will depend on overcoming technical hurdles, significantly lowering the cost and gaining application and building code acceptance. Currently, vacuum panels are only SNAP approved for the rigid polyurethane appliance sector (Tao *et al.*, 1996; Dieckmann and Magid, 1999; Honeywell, 2000b).

More research is needed to determine the potential of these alternative technologies to displace foams blown using high-GWP gases. Because reliable cost information is not available, these HFC emission reductions are not discussed further.

Direct Emission Reduction

Direct emission reduction opportunities vary according to the type of foam in question and the application to which it is put. Various measures could be adopted in each of the phases of production, usage, and decommissioning. Examples include capture of the vapor at the “head” and use of lower permeability facings. Proper recovery and recycling or destruction by means of incineration are also potential means of abating HFC emissions. It is difficult to generalize the potential emission savings or costs associated with these abatement options (March Consulting Group, 1998). However, recovery at de-commissioning currently is not considered economically or technologically feasible. Consequently, this reduction option is not discussed further.

10. Cost and Emission Reduction Analysis of HFC Emissions from Aerosols in the United States

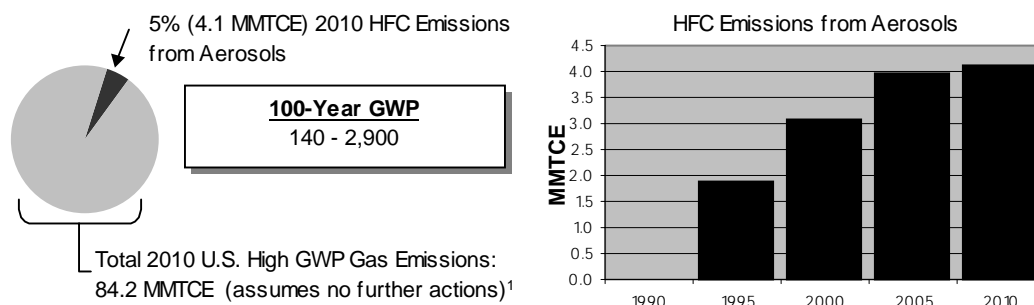
10.1 Introduction

Various hydrofluorocarbons (HFCs) are used as propellants in aerosol applications. These include HFC-134a, HFC-152a, and HFC-227ea, with 100-year GWPs of 1,300, 140, and 2,900 times the warming potential of carbon dioxide, respectively. Under a business-as-usual scenario, by 2010, the U.S. would be expected to emit over four MMTCE of these HFCs from the use of aerosols if further reduction efforts are not made (see Exhibit 10.1).¹

Metered dose inhalers (MDIs) will account for one-third of all aerosol HFC equivalent emissions by 2010, representing about 1.4 MMTCE. Inhaled therapies, primarily MDIs, are critically important in the treatment of asthma and chronic obstructive pulmonary disease (COPD), each affecting millions of Americans (American Lung Association, 2000). Historically, the majority of MDIs have used CFCs as the propellant. However, as a result of initiatives under the Montreal Protocol on Substances that Deplete the Ozone Layer and the subsequent phaseout of CFC production under the Clean Air Act in 1996, pharmaceutical companies that produce MDIs have committed to develop alternatives to CFC-based MDIs. Despite these commitments, EPA estimates that over 90 percent of the MDI industry still uses CFCs as the aerosol propellant. Because MDIs are medical devices, substitute propellants must meet far stricter performance and toxicology specifications than would be required in most other end products. Further, each MDI that is re-formulated with an alternative propellant must be approved by the Food and Drug Administration prior to entering the market.

The pharmaceutical aerosol industry currently is working to develop HFC-propellant metered dose inhalers. The earliest non-CFC substitute products, two of which earned FDA approval before January 2001, use HFC-134a, but eventually the industry expects products to utilize HFC-227ea, as well. In addition to MDIs that

Exhibit 10.1: U.S. Historical and Baseline HFC Emissions from Aerosols



¹ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

use propellants, dry powder inhalers (DPIs) can be used as a substitute for some MDIs. However, DPIs can replace only a small portion of the market.

In addition to metered dose inhalers, HFC aerosols are becoming more widely used in various consumer products and specialty market applications. After the CFC aerosol ban in 1977, many consumer products such as spray deodorants and hair sprays were either reformulated with hydrocarbon propellants or replaced with not-in-kind substitutes such as pump sprays or solid and roll-on deodorants. Now, with the advent of HFC propellants, particularly HFC-152a, chemical manufacturers are marketing HFCs for use in consumer products. HFC-152a is preferred over HFC-134a due to its lower cost and GWP, but HFC-134a is still used in nearly half of the non-MDI aerosol market, in niche specialty markets such as electronic equipment dusters, boat and safety “air” horns, and tire inflators (Dieckmann and Magid, 1999). In general, HFCs hold a small share of the consumer aerosols market, concentrated mostly in applications where volatile organic compound (VOC) emissions and their impact on urban air quality are a concern. The aerosols industry has a strong incentive to use HFCs responsibly. If HFC use is accelerated, increased public concern may be result (UNEP, 1999).

10.2 Historical and Baseline HFC Emission Estimates

EPA uses a detailed Vintaging Model of ozone-depleting substance (ODS) containing equipment and products to estimate the use and emissions of various ODS substitutes. The model tracks the use and emissions of various compounds for the annual “vintages” of new equipment that enter service in each end-use. (See Appendix A for a full description of the Vintaging Model.) Aerosols represent one of the major end-use categories defined in the Vintaging Model to characterize ODS substitute use in the U.S. (see Exhibits 10.2 and 10.3). There are several regulatory programs in place (e.g., Significant New Alternatives Policy Program determines the acceptability of substitutes to ODS) to limit use of ODS substitutes in some applications. These actions are expected to result in significant reductions in ODS substitute emissions. These reductions are incorporated in the baseline estimate of emissions. The cost analysis presented here evaluates the cost of reducing emissions from this baseline.

Exhibit 10.2: Historical U.S. HFC Emissions from Aerosols (1990-1999)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	<0.05	<0.05	<0.05	<0.05	<0.05	1.9	2.1	2.5	2.6	2.9

Source: EPA, 2000 (for 1990-1998) and EPA estimates (for 1999).

Notes:

Emissions are not broken down by chemical to avoid disclosure of confidential business information.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the report.

The sudden increase in MMTCE is because HFC-134a began to penetrate the non-MDI aerosol market in 1994-1995.

Exhibit 10.3: Baseline U.S. HFC Emissions from Aerosols (2000-2010)

	2000	2005	2010
Emissions (MMTCE)	3.08	3.95	4.10

Notes:

Forecast emissions are based on a business-as-usual scenario, assuming no further action.

Emissions are not broken down by chemical to avoid disclosure of confidential business information.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the report.

Non-MDI use accounts for the majority of the HFC-134a emissions (mainly for specialty end uses) and all of the HFC-152a emissions (mostly formulated consumer products), while MDI use accounts for all emissions of HFC-227ea. The estimates presented in Exhibit 10.3 were developed with the following major assumptions:

- Penetration of HFCs into the MDI end use;
- Continued growth of HFC-134a use in specialty markets; and
- Minimal impact of penetration of additional HFCs into consumer end use applications.²

10.3 HFC Emission Reduction Opportunities

Metered Dose Inhalers

As MDIs are transitioned away from use of CFCs, both HFC propellants and dry powder inhalers are being developed. Although hydrocarbons have replaced CFCs as propellants in many commercial aerosols, they have been found to be unacceptable for use in MDIs (IPAC, 1999). Dry powder inhalers (DPIs) have been successfully used with most anti-asthma drugs, although they are not successful with all patients or all drugs. Micronised dry powder can be inhaled and deposited in the lungs from DPIs as with MDIs, but only in patients who are able to inhale robustly enough to transport the powder to the lungs. DPIs are not suitable for persons with severe asthma or for young children. Unlike MDIs, powdered drug particles contained in DPIs tend to aggregate and may cause problems in areas with hot and humid climates (March Consulting Group, 1999). In 1999, DPI usage in the United States was estimated to represent less than two percent of all inhaled medication. However, DPIs may represent a viable alternative, as suggested by their increased use in Europe, for example in Sweden, where they account for 85 percent of inhaled medication. Globally, DPIs are estimated to be growing at a rate of 15 percent annually. Even with anticipated strong market growth, however, DPI use will still be less than MDI (combined HFC and CFC) use in 2005 (UNEP, 1999). There is a trend towards development of a broad range of novel oral treatments that would be swallowed, rather than inhaled, and may be introduced over the next 10 to 20 years. These new medications may impact MDI use although it is not expected that they would completely replace inhaled MDI therapy.

It is important to note that the type of propellant used in MDIs is a medical decision involving the pharmaceutical industry, the FDA, and ultimately doctors and their patients who will be involved in selecting the method of therapy that proves most effective for particular individuals.

Specialty Products

Specialty aerosol end-uses include tire inflators, electronics cleaning products, dust removal, freeze spray, signaling devices, and mold release agents. HFCs are currently used when flammability issues cannot easily be overcome. Examples include tire inflators and air signaling horns, that use HFC-134a to avoid potential explosivity that could occur when using highly flammable propellants (Dieckmann and Magid, 1999). HFC-152a has been utilized in dusters since 1993 and continued substitution of HFC-134a with HFC-152a is a reduction strategy that has had significant success thus far, and is expected to continue.

Consumer Products

Formulated consumer products include hairsprays, mousse, deodorants and anti-perspirants, household products, spray paints, and automotive products. Many of these products utilize HFCs in order to comply with regulations that reduce allowable VOC content. The following replacement options exist for consumer aerosol products:

² The State of California and at least eight other states are considering further limiting the use of VOCs in consumer products, in which case a subset of the aerosol market may switch to HFC propellants. However, as stated previously, the high cost of HFCs, the low GWP of HFC-152a, and the potential for consumer concerns will most likely limit this transition considerably. To the extent that this does occur, the emissions presented in Exhibit 10.3 may be slightly underestimated.

- **Not-in-kind (NIK) alternatives.** These include finger/trigger pumps, powder formulations, sticks, rollers, brushes, nebulizers, and bag-in-can/piston-can systems that could displace HFCs, and often prove to be a better and more cost-effective option than HFC-propelled aerosols. Particularly in areas where a unique HFC property is not specifically needed for a certain end-use, NIK alternatives are the best option.
- **Hydrocarbon aerosol propellants.** These are usually mixtures of propane, butane, and isobutane, and are also an inexpensive choice for propellants in consumer products. Their costs average less than one tenth the cost of HFCs. The main disadvantages of hydrocarbon aerosol propellants are flammability and VOC emission concerns. Hydrocarbons are the primary propellant in the non-MDI aerosol market and could probably hold a larger share than is forecast by the Vintaging Model. If HFC-134a and HFC-152a use could be replaced with hydrocarbon use, then reductions in greenhouse gas emissions would result.
- **Dimethyl ether.** Dimethyl ether is a flammable alternative aerosol propellant. While it is a VOC, it has excellent solvency and water compatibility.
- **Compressed gases.** Gases such as CO₂, N₂, compressed air, or nitrous oxide may be used in a few aerosol applications, but these are often less effective because the propellant pressure gradually falls as the aerosol can is emptied (March Consulting Group, 1998). However, these gases are non-flammable and do not require the use of extra explosion-proof equipment. In addition, technological improvements have been made to offset the effects of decreased pressure through innovative valve configurations and proper selection of compatible solvents (UNEP, 1998).
- **Substituting for lower GWP HFCs.** Replacement of higher GWP HFCs, such as HFC-134a, with a lower GWP HFC, such as HFC-152a, will greatly reduce emissions from the aerosols sector. HFC-152a, for instance, possesses only moderate flammability hazards and might therefore be acceptable for some applications.

10.4 Cost Analysis

Metered Dose Inhalers

Given the unique medical requirements for developing metered dose inhalers, and the fact that the industry is just beginning to introduce HFC alternatives after investing heavily in the development of HFC technologies, an aerosol replacement for HFC-based MDIs is unlikely to be developed within the time frame of this analysis. Furthermore, the cost to develop and market FDA-approved HFC-based MDIs is expected to be very high. The industry has spent approximately \$1 billion developing MDIs using HFC-134a or HFC-227ea and expects to spend more to complete the development process (IPAC, 1999). If an alternative to HFC propellants could be developed, which is uncertain, the cost would likely exceed that of the CFC phaseout for MDIs. Assuming a 20 percent market penetration in 2005, which ramps up to 100 percent of the market in 2009, the incremental cost for reducing greenhouse gas emissions from MDIs would still be in the range of hundreds of dollars per metric ton of carbon equivalent.

To the extent that health and technical concerns are adequately met, a transition of inhalation therapy away from propellant MDIs and toward NIK alternatives may occur over the next 10 to 20 years. This will provide patients with a wider variety of choices, lower overall costs of MDIs, and potential displacement of CFC use. The rapidity at which these changes will occur is contingent upon product development cycles (generally about 10 years), cost-effectiveness, and manufacturing capacity. In the United States alone, over 150 patents for new alternatives have been filed over the past 10 years (UNEP, 1999).

Other General Aerosols

The most viable options to reduce HFC emissions from aerosols are hydrocarbon aerosol propellants and not-in-kind replacements. All cost analyses are based on either a four percent discount rate or an eight percent discount rate and a 10-year project lifetime. Financial assumptions and results specific to each emission reduction option are presented below. Exhibit 10.4 summarizes the potential emission reductions and associated costs of both options.

Exhibit 10.4: Emission Reductions and Cost in 2010

Option	Break-even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate		MMTCE	Percent	MMTCE	Percent
	4%	8%				
Hydrocarbon Aerosol Propellants	(20.35)	(20.32)	0.23	6%	0.23	6%
Not-in-kind Replacements	(19.15)	(19.12)	0.47	11%	0.70	17%
HFC replacement	(8.14)	(8.09)	0.82	20%	1.52	37%

Notes:

2010 baseline HFC emissions from aerosols equal 9,246 metric tons HFC or 4.10 MMTCE.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the report.

Parentheses indicate savings.

Sums might not add to total due to rounding.

Hydrocarbon Aerosol Propellants. The capital costs of converting filling facilities to accept hydrocarbon propellants range from \$150,000 to \$1,750,000. However, since the hydrocarbon prices are generally lower than the cost of HFCs, production costs are less. While both hydrocarbon and DME aerosol propellants have already been utilized significantly, it was assumed that they could displace only 10 percent of the non-MDI HFC aerosol market, given VOC and flammability concerns. Based on these factors, in 2010 this option could reduce emissions by 0.23 MMTCE or six percent of baseline emissions at a cost savings of \$20.35 per metric ton of carbon equivalent (TCE) and \$20.32/TCE for four and eight percent discount rates, respectively.

NIK Replacements. There is significant variability in financial components of projects targeting NIK replacements for HFC-containing aerosol products. This is due to the wide range of potential aerosol and NIK product types. In the case of liquid pumps and solid applicators, capital investments are lower but material costs will be higher (UNEP, 1998). For this analysis, an incremental capital cost of \$250,000 was used with annual costs estimated at around \$500,000, based on an annual throughput of 10 million units. Despite the costs of this option, an overall savings of almost \$4,000,000 per year would result, due primarily to the avoidance of HFC costs. It was assumed that approximately 20 percent of the non-MDI HFC aerosol market could be displaced with NIK products. Based on the above factors, NIK options can reduce emissions by 0.47 MMTCE in 2010 or 11 percent of baseline emissions at a cost savings of \$19.15/TCE and \$19.12/TCE for four and eight percent discount rates, respectively.

Replacement with lower GWP HFC alternatives. The capital costs of converting filling facilities to accept HFC-152a may range in the area of \$500,000 (Lueszler, 2000). It is estimated that through its use, approximately 50 percent of the non-MDI market may be captured. Also, the lower price per pound of HFC-152a, \$2.15/lb, will result in significantly lower production costs (ICF Consulting, 2000). The incremental emission reduction of this option is 0.82 MMTCE, or 20 percent of the 2010 baseline emission of 4.10 MMTCE. Based on these factors, switching to the HFC-152a option can reduce emissions at a cost savings of \$8.14/TCE and \$8.09/TCE for four and eight percent discount rates, respectively.

10.5 References

American Lung Association. 2000. *Asthma Trends in Morbidity and Mortality 2000*. (Available on the Internet at <http://www.lungusa.org/data/>).

Dieckmann, J., and H. Magid. 1999. *Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air-Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications*. Final Report to the Alliance for Responsible Atmospheric Policy. Arthur D. Little, Inc., Cambridge, MA; Reference Number 49648.

EPA. 2000. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1998*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC; EPA 236-R-00-001. (Available on the Internet at <http://www.epa.gov/globalwarming/emissions/national/download.html>).

ICF Consulting. 2000. Data collected from gas suppliers, Washington, D.C., July 2000.

IPAC. 1999. *The Reformulation of MDIs*. (Available on the Internet at <http://www.ipacmdi.com/Reformation.html>).

IPAC. 1999. *Ensuring Patient Care 2nd Edition* (Available on the Internet at <http://www.ipacmdi.com/Ensuring.html>).

Lueszler, John. 2000. Personal communication. Dupont, July 2000.

March Consulting Group. 1998. *Opportunities to Minimize Emissions of Hydrofluorocarbons (HFCs) from the European Union*. Final Report. Prepared by March Consulting Group, United Kingdom.

March Consulting Group. 1999. *UK Emissions of HFCs, PFCs, and SF₆ and Potential Emission Reduction Options*. Final Report. Prepared by March Consulting Group, United Kingdom.

UNEP. 1998. *Montreal Protocol on Substances that Deplete the Ozone Layer, Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride Technical Options Committee: 1998 Assessment*. UNEP Ozone Secretariat, Nairobi, Kenya.

UNEP. 1999. *The Implications to the Montreal Protocol of the Inclusion of HFCs and PFCs in the Kyoto Protocol*. HFC and PFC Task Force of the Technology and Economic Assessment Panel.

11. Cost and Emission Reduction Analysis of HFC and PFC Emissions from Fire Extinguishing in the United States

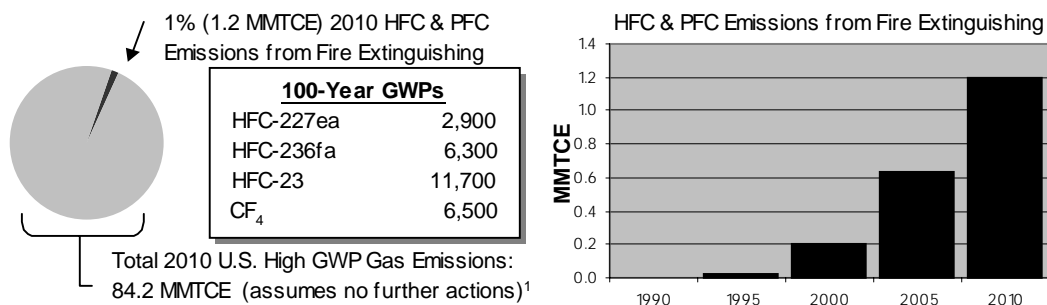
11.1 Introduction

The principal greenhouse gases emitted from fire extinguishing systems are hydrofluorocarbons (HFC-227ea, HFC-236fa, HFC-23) and perfluoromethane (CF₄). These gases have 100-year global warming potentials (GWPs) that are several thousand times the GWP for carbon dioxide (see Exhibit 11.1). Emissions of these gases from fire extinguishing systems in the United States are forecast to reach over one MMTCE in 2010 under a business-as-usual scenario if further reduction efforts are not made (see Exhibit 11.1).¹

These high GWP gases are substitutes for halons, Class I ozone-depleting substances (ODS) that have been widely used in fire-extinguishing applications in the United States. Although halons were produced in much lower volumes than other ODS, they have extremely high ozone depletion potentials (ODP) due to the presence of bromine, which reacts more strongly with ozone than chlorine. Halons are used in fire suppression and explosion protection applications because they are electrically non-conductive, dissipate rapidly without residue, are safe for limited human exposure, and are extremely efficient in extinguishing most types of fires (EPA, 1994).

Halon applications in the United States can be divided into two categories: (1) portable fire extinguishers (streaming) that originally used Halon 1211, and (2) total flooding applications that originally used Halon 1301 (March Consulting Group, 1998 and 1999). SF₆ was used in fire extinguishing systems for testing purposes to a small extent by the Navy, but for the most part is no longer used in any capacity in the fire protection sector.

Exhibit 11.1: U.S. Historical and Baseline HFC and PFC Emissions from Fire Extinguishing



Portable fire extinguishers are most frequently used in offices, manufacturing and retail facilities, aerospace/marine applications, and homes. With the implementation of the halon production phaseout in

¹ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

the UNITED STATES, about 80 percent² of new portable fire extinguishing units are now manufactured with non-ODP/low-GWP alternatives such as dry powder, carbon dioxide, or water in place of Halon 1211. HCFC blends are also used. Market penetration of HFCs in this sector has been limited, and is unlikely to grow except in certain specialized applications (e.g., marine, aviation, and military applications). PFCs have had a very small penetration in the portable fire extinguisher market. By 2010, only two HFCs, HFC-236fa and HFC-227ea, are expected to be used to a limited extent as replacements in small segments of the portable extinguishing sector.

Total flooding systems are usually used for fixed-site systems to protect a variety of spaces, including:

- electronic and telecommunications equipment, such as tape storage areas, computer facilities, telecommunications gear, medical facilities, control rooms in nuclear power plants, and air traffic control towers;
- military applications, including aviation engine nacelles and dry bays, naval engine compartments and flammable liquid storage areas, and engine compartments and occupied crew spaces of ground combat vehicles;
- oil production facilities;
- flammable liquid storage areas;
- engine nacelles and cargo bays of commercial aircraft;
- cultural institutions and museums;
- records storage areas;
- bank vaults;
- warehouses; and
- special facilities, such as research laboratories and high-security military facilities.

Halon 1301 was historically used in applications where human exposure to the agent was likely, because the fire extinguishing concentration was safe for limited, acute human exposures. HFC-227ea is the primary halocarbon that has replaced Halon 1301 in these applications. Inert gas systems that contain varying amounts of nitrogen, argon, and carbon dioxide are also being used in these applications. Other HFCs, such as HFC-23 and HFC-236fa, that are also safe for limited, acute human exposures, are being used in smaller amounts due to environmental, technical, and economic reasons. Use of HFC-125 has been limited to normally non-occupied specialty applications, such as aviation engine nacelles. New methods to determine safe concentrations for limited, acute human exposure have recently been adopted in the National Fire Protection Association (NFPA) 2001 Standard on Clean Agent Fire Extinguishing Systems, and may allow the use of HFC-125 and other agents in additional applications. A very small number of telecommunications facilities are also using PFCs. A variety of non-ODP/non-GWP alternative technologies are also being used in various applications that formerly used Halon 1301. Not-in-kind alternative technologies are also available, including powdered aerosols, water sprinklers, water mist systems, and foams.

² Estimated from EPA's Vintaging Model.

11.2 Historical and Baseline HFC and PFC Emission Estimates

EPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes, including HFCs and PFCs. (See Appendix A for a full description of the Vintaging Model.) Historic HFC and PFC emissions from both portable fire extinguishing and total flooding systems totaled 0.02 MMTCE in 1995 (Exhibit 11.2). Baseline estimates for the years 2000, 2005, and 2010 shown in Exhibit 11.3 are also based on estimates from the Vintaging Model. These estimates do not distinguish between emissions from servicing, leaks, accidental/false discharges, or intentional discharges to extinguish fires. There are several regulatory programs (e.g., Significant New Alternatives Policy (SNAP) program) in place that limit the use of ODS substitutes in some applications, which have resulted in reductions in ODS substitute emissions. These reductions are incorporated in the baseline estimates. The cost analysis presented here evaluates the cost of reducing emissions from this baseline.

Exhibit 11.2 Historical U.S. HFC and PFC Emissions from Fire Extinguishers (1990-1999)										
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.06	0.10	0.15
Source: EPA, 2000 (for 1990-1998) and EPA estimates (for 1999).										
Notes:										
Emissions are not broken down by chemical to avoid disclosure of confidential business information.										
Conversion to MMTCE is based on the GWPs listed in the Introduction to this report.										

Exhibit 11.3: Baseline U.S. HFC and PFC Emissions from Fire Extinguishers (2000-2010)			
	2000	2005	2010
Emissions (MMTCE)	0.20	0.64	1.20
Notes:			
Emissions are not broken down by chemical to avoid disclosure of confidential business information.			
Conversion to MMTCE is based on the GWPs listed in the Introduction to this report.			
Approximately 80 percent of total emissions in 2010 are attributable to total flooding applications, whereas 20 percent are attributable to portable system applications.			
Forecast emissions are based on a business-as-usual scenario, assuming no further action.			

11.3 HFC and PFC Emission Reduction Opportunities

The existing options for reducing HFC and PFC emissions from the fire protection sector include the use of alternative fire protection agents and the use of alternative technologies and practices. The remainder of this section discusses use options.

Use of Alternative Fire Protection Agents

Inert gases and water mist systems that provide an equivalent level of both fire protection and life safety/health protection could be considered as alternatives to some HFC use in total flooding applications. Carbon dioxide in total flooding systems has been in use for many years. Due to the lethal concentrations at which carbon dioxide is required for use as a fire extinguishing agent (at least 34 percent), safety standards regulate its use in occupied areas. The NFPA 12 Standard requires safeguards such as predischARGE alarms and time delays to ensure prompt evacuation prior to discharge, prevent entry into areas where carbon dioxide has been discharged, and provide means for prompt rescue of any trapped personnel. Likewise, the International Maritime Organization's Safety of Life at Sea (SOLAS) standard does not prohibit the use of carbon dioxide in normally occupied areas, but calls for the use of suitable alarms and mandates against the use of automatic release of the fire-extinguishing medium, as

specified in EPA (2000). According to the NFPA, some of the types of hazards and equipment that carbon dioxide systems protect are “flammable liquid materials; electrical hazards, such as transformers, switches, circuit breakers, rotating equipment, and electronic equipment; engines utilizing gasoline and other flammable liquid fuels; ordinary combustibles, such as paper, wood, and textiles; and hazardous solids” (NFPA 12). Because carbon dioxide systems are more economical than the use of HFCs, a small niche market has been carved for carbon dioxide in the total flooding sector. While carbon dioxide systems will continue to be used in narrow use flooding applications, where permitted by regulatory, liability and safety/health standpoints, it is assumed that carbon dioxide will not displace any use of HFCs in this sector.

Use of Alternative Technologies and Practices

In addition to installing alternative systems, improved fire prevention technologies may be used to reduce HFC and PFC emissions. Some oil and gas processing facilities in Alaska’s Arctic North Slope region have begun installing early warning smoke detection, infrared cameras (to better distinguish real fires from false alarms), and other technologies that can either reduce the amount of agent discharged to prevent a fire or prevent a discharge altogether. There may also be opportunities to reduce emissions from portable fire extinguishers during training procedures, by using simulators or training videos rather than actual system discharges.

Available alternatives to reduce emissions in the fire protection sector may not be technically or economically viable for all end use applications. For example, military applications often have very specialized needs (due in part to issues of national security and the potential for combat situations) that do not exist in other end-use applications. Similarly, applications that are space and/or weight constrained, such as marine and aviation applications, may be more limited in their choice of alternative agents. Electronic and telecommunication applications which represent the largest use of HFCs in the total flooding sector, offer the greatest opportunities to consider potential alternatives, albeit with significant potential economic and technical penalties.

11.4 Cost Analysis

This cost analysis focuses on total flooding applications. Based on projections from the Vintaging Model, these applications will account for about three-quarters of the weighted high GWP gas emissions from fire extinguishing systems in 2010. Outlined below are two potential options for reducing emissions of high GWP gases from total flooding systems.

The first option is the use of zero GWP inert gas systems. Costs are determined relative to typical HFC-227ea systems, as they predominate in the HFC market. Inert gas systems would be suitable in the electronics/telecommunications applications and other Class A surface fire hazards that represent an estimated 95 percent of the total flooding sector. It was estimated that inert gas systems could displace up to 45 percent of HFC use. Installation costs for inert gases were assumed to be ten percent higher than for HFCs on an equivalent volume of protected space basis. Inert gas systems require significantly more storage space for agent cylinders, since a greater amount of inert gas is needed per unit volume of protected space, as compared to HFC-227ea. The one-time cost to build or rent additional space (assumed to be \$150 per square foot) and annual heating and cooling costs (assumed to be \$8 per square foot) are included. As shown below, this option could reduce total emissions from the fire extinguishing sector (including streaming) by 25 percent.

The second option is the use of water mist systems. These systems could provide equivalent fire protection and life safety/health protection for Class B fuel hazards where low temperature freezing is not a concern. Installation costs for water mist systems are estimated to be 75 percent of the cost of an HFC system, representing large cost savings. Because of the significant cost savings, it is estimated that water mist systems could replace up to five percent of the total flooding applications of HFCs, which is the estimated percent of Class B applications in the total flooding market. As shown in Exhibit 11.4, water mist systems could reduce total emissions in the fire extinguishing sector by three percent.

The cost analyses were performed for four- and eight-percent discount rates, both with a ten-year project lifetime. Exhibit 11.4 summarizes HFC emission reductions by cost per metric ton of carbon equivalent (TCE). As shown, 27 percent of total flooding emission reductions from the baseline can be achieved in 2010.

Exhibit 11.4: Emission Reductions and Cost in 2010						
Option	Break-Even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate		MMTCE	Percent	MMTCE	Percent
	4%	8%				
Water Mist Systems	(16.19)	(19.42)	0.03	3%	0.03	3%
Inert Gas Systems	53.86	61.44	0.29	25%	0.33	27%

Note:
 2010 baseline emissions from the fire extinguishing sector equal 1.2 MMTCE.
 Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.
 Sums might not add to total due to rounding.

11.5 References

EPA. 1994. SNAP Technical Background Document: Risk Screen on the Use of Substitutes for Class I Ozone-Depleting Substances: Fire Suppression and Explosion Protection (Halon Substitutes).

EPA. 2000. *Carbon Dioxide as a Fire Suppressant: Examining the Risks*. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC. EPA430-R-00-002.

EPA. 2001. *Inventory of Greenhouse Gas Emissions and Sinks 1990-1999*. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC; EPA 236-R-01-001. (Available on the Internet at <http://www.epa.gov/globalwarming/emissions/national/download.htm>).

March Consulting Group. 1998. *Opportunities to Minimize Emissions of Hydrofluorocarbons (HFCs) from the European Union*. Final Report. Prepared by March Consulting Group, UK.

March Consulting Group. 1999. *UK Emissions of HFCs, PFCs, and SF₆ and Potential Emission Reduction Options*. Final Report. Prepared by March Consulting Group, United Kingdom.

NFPA 12. *Standard on Carbon Dioxide Extinguishing Systems*. 1998 Edition. National Fire Protection Association, Quincy, MA.

Appendix A. Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances

A. Overview

The Vintaging Model was developed as a tool for estimating the annual chemical emissions from industrial sectors that have historically used ozone-depleting substances (ODS) in their products. Under the terms of the Montreal Protocol and the Clean Air Act Amendments of 1990, the domestic production of ODS – chloroflourocarbons (CFCs), halons, carbon tetrachloride, methyl chloroforms, and hydrochlorofluorocarbons (HCFCs) – has been drastically reduced, forcing these industrial sectors to transition to more ozone friendly chemicals. As these industries have moved toward ODS alternatives such as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), the Vintaging model has evolved into a tool for estimating the rise in consumption and emissions of these alternatives, and the fall of ODS consumption and emissions.

The Vintaging model, named for its method of tracking the emissions of annual “vintages” of new equipment that enter into service, is a “bottom-up” model. It models use and emissions of chemicals based on estimates of the quantity of equipment or products sold each year containing these chemicals, and the amount of chemical required to manufacture and/or maintain equipment and products over time. As ODS are phased out, a percentage of the market share originally occupied by the ODS is allocated to each of its substitutes.

The model estimates emissions from six end-use categories: refrigeration and air-conditioning, foams, aerosols, solvents, fire extinguishing, and sterilization. Within these categories, there are over 40 independently modeled end-uses. The model requires input regarding the market growth for each of the end-uses, as well a history of the market transition from ODS to alternatives. For the purpose of projecting the use and emissions of chemicals into the future, the model incorporates the available information about probable evolutions of the end-use market.

The Vintaging model makes use of this market information to build an inventory of the in-use stocks of the equipment in each of the end-uses. This includes the percentage of the equipment stock that contains each chemical. These modeled stock inventories are maintained through the annual addition of new equipment and the retirement of equipment after an appropriate number of years. Annual leak rates, servicing emissions, and disposal emissions are estimated for each of the end-uses. It is through these emissions, occurring throughout the lifetime of the equipment, that the lag between consumption of chemical and actual emission of chemical is created. By aggregating the emission and consumption output over the different end-uses, the model produces estimates of total annual use and emissions of each chemical.

The Vintaging Model synthesizes data from a variety of sources, including data from the ODS Tracking System maintained by the Stratospheric Protection Division and information from submissions to EPA under the Significant New Alternatives Policy (SNAP) program. Published sources include documents prepared by the United Nations Environment Programme (UNEP) Technical Options Committees, reports from the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), and conference proceedings from the International Conferences on Ozone Protection Technologies. EPA also coordinates extensively with numerous trade associations and individual companies. For example, the Alliance for Responsible Atmospheric Policy, the Air-Conditioning and Refrigeration Institute, the Association of Home Appliance Manufacturers, the American Automobile Manufacturers Association,

and many of their member companies, have provided valuable information over the years. In some instances the unpublished information that the EPA uses in the model is classified as Confidential Business Information (CBI). While in most cases the annual emissions inventories and projections of chemicals are aggregated in such a way that CBI cannot be inferred, there are times when additional aggregation is necessary to protect sensitive data. Full public disclosure of the inputs to the Vintaging model would jeopardize the security of the CBI that has been entrusted to the EPA.

Within the context of the Cost of Emissions Reductions Analysis, the Vintaging model was used exclusively to project the emissions reductions that could be expected from the mitigation techniques outlined in the body of the report. These projected reductions were then used to create the marginal abatement curves also contained in the body of the report. Two types of projections are necessary to calculate the reductions: “baseline” emissions and model scenarios that reflect the proposed mitigation techniques. A “baseline” is a measure of the emissions that would be expected if no mitigation techniques were to enter into practice. Reductions are defined as the difference between these two projections.

The following sections discuss the forms of the emission estimating equations used in the Vintaging model for each broad end-use category.

B. Emission Equations

Refrigeration and Air-Conditioning

For refrigeration and air conditioning products, emission calculations are split into two categories: emissions during equipment lifetime, which arise from annual leakage and service losses, and disposal emissions, which occur at the time of discard. For each year, the model tracks which vintages are in use, which are being discarded, how much of each chemical is being recycled, what chemicals are in each vintage, and at what rates these chemicals are emitted. Equation 1 calculates the lifetime emissions from leakage and service, and Equation 2 calculates the emissions resulting from disposal of the equipment. These lifetime emissions and disposal emissions are summed across each vintage to establish the total emissions from refrigeration and air-conditioning for a given year (Equation 3). As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates.

Lifetime emissions from any piece of equipment include both the amount of chemical leaked during equipment operation and during service recharges. Emissions during emissions from leakage and servicing can be expressed as follows:

$$E_{ES} = U_{ES} * C_{ES} * (LR_{ES} + SR_{ES}) * PC_{ES} \quad \text{Eq. 1}$$

Where:

- E_{ES} = *Emissions from Equipment Serviced.* Emissions from a specific chemical in a given year from equipment leaks and service (recharging) for a particular type of refrigeration equipment.
- U_{ES} = *Units of Equipment in Service.* Number of equipment units in service in a given year for a particular type of refrigeration equipment.
- C_{ES} = *Charge of Equipment in Service.* Average charge of a specific chemical for equipment units in service in a given year, in Kg. Equal to the average charge when equipment units were newly manufactured.
- LR_{ES} = *Leak Rate of Equipment in Service.* Annual average leak rate as a percent of the average charge of a specific chemical for equipment units in service in a given year for a particular type of refrigeration equipment.
- SR_{ES} = *Service Rate of Equipment in Service.* Average emissions at service (amount of charge lost) as a percent of the average charge of a specific chemical for equipment units in service

in a given year for a particular type of refrigeration equipment.

PC_{ES} = *Penetration of Chemical in Equipment in Service.* Amount of a specific chemical as a percentage of all chemicals used in equipment units in service in a given year for a particular type of refrigeration equipment. In other words, this is the market penetration, in percent terms, of any ODS substitute in a given end-use.

The disposal emission equations assume that a certain percentage of the chemical consumed in a particular year will be emitted to the atmosphere when that vintage is discarded. Disposal emissions are thus a function of the number of units being disposed and the proportion of chemical released at disposal:

$$E_{ED} = U_{ED} * C_{ED} * PC_{ED} * [1 - (CR_{ED} * CRR_{ED})] \quad \text{Eq. 2}$$

Where:

E_{ED} = *Emissions from Equipment Disposed.* Emissions of a specific chemical in a given year from equipment disposal, for a particular type of refrigeration equipment.

U_{ED} = *Units of Equipment Disposed.* Number of equipment units being retired in a given year for a particular type of refrigeration operation.

C_{ED} = *Charge of Equipment Disposed.* Average charge of a specific chemical for equipment units being retired in a given year by weight. Equal to the average charge when equipment units were newly manufactured.

PC_{ED} = *Penetration of Chemical in Equipment Disposed.* Amount of a specific chemical, as a percentage of all chemicals used in equipment units being retired, in a given year for a particular type of refrigeration equipment.

CR_{ED} = *Chemical Remaining.* Amount of a specific chemical remaining in equipment units being retired in a given year, as a percentage of the average charge size, for a particular type of refrigeration equipment.

CRR_{ED} = *Chemical Recovery Rate.* Percent of chemical recovered from equipment being retired as a percentage of chemical remaining, for a particular type of refrigeration equipment in a given year.

$$E_T = E_{ES} + E_{ED} \quad \text{Eq. 3}$$

Where:

E_T = *Total Emissions.* Emissions of a specific chemical in a given year for a particular type of refrigeration equipment.

E_{ES} = *Emissions from Equipment Serviced.* Emissions from a specific chemical in a given year from equipment leaks and service (recharging) for a particular type of refrigeration equipment.

E_{ED} = *Emissions from Equipment Disposed.* Emissions of a specific chemical in a given year from equipment disposal for a particular type of refrigeration equipment.

Aerosols

All HFCs and PFCs used in aerosols are assumed emitted in the year of manufacture. Since there is currently no aerosol recycling, it is assumed that all of the annual production of aerosol propellants is released to the atmosphere. Equation 4 describes the emissions from the aerosols sector.

$$E = QC \quad \text{Eq. 4}$$

Where:

E = *Emissions.* Total emissions of a specific chemical in a given year from use in aerosol products, by weight

QC = *Quantity of Chemical.* Total quantity of a specific chemical contained in aerosol products sold in the given year, by weight

Solvents

Generally, most solvents used are assumed to remain in the liquid phase and are not emitted as gas. Thus, emissions are considered “incomplete,” and are set as a fraction of the amount of solvent consumed in a year. For solvent applications, a fixed percentage of the new chemical used in equipment is assumed emitted in that year. The remainder of the used solvent is assumed to be reused or disposed without being released to the atmosphere. Equation 5 calculates emissions from solvent applications.

$$E = L * QC$$

Eq. 5

Where:

- E = *Emissions*. Total emissions of a specific chemical in a given year from use in solvent applications, by weight.
- L = *Percent Leakage*. The percentage of the total chemical that is leaked to the atmosphere.
- QC = *Quantity of Chemical*. Total quantity of a specific chemical sold for use in solvent applications in the given year, by weight.

Fire Extinguishing

Total emissions from fire extinguishing are assumed, in aggregate, to equal a percentage of the total quantity of chemical in operation at a given time. For modeling purposes, it is assumed that fire extinguishing equipment leaks at a constant rate for an average equipment lifetime. This percentage varies for streaming (Equation 6) and flooding (Equation 7) equipment.

(i) Streaming Equipment

$$E = L * \sum QC_i \text{ For } i = (j-x) \text{ to } j$$

Eq. 6

Where:

- x = The average lifetime of the equipment.
- j = Index of the given year.
- E = *Emissions*. Total emissions of a specific chemical in a given year for streaming fire extinguishing equipment, by weight.
- L = *Percent Leakage*. The percentage of the total chemical in operation that is leaked to the atmosphere.
- QC = *Quantity of Chemical*. Total amount of a specific chemical used in new streaming fire extinguishing equipment in a given year, j, by weight.
- $\sum QC_i$ = *Sum of Quantity of Chemical over Multiple Years*. Total amount of a specific chemical used in new streaming fire extinguishing equipment from year (j-15) to year j, by weight.

(ii) Flooding Equipment

$$E = L * \sum QC_i \text{ For } i = (j-x) \text{ to } j$$

Eq. 7

Where:

- x = The average lifetime of the equipment.
- j = Index of the given year.
- E = *Emissions*. Total emissions of a specific chemical in a given year for flooding fire extinguishing equipment, by weight.
- L = *Percent Leakage*. The percentage of the total chemical in operation that is leaked to the atmosphere.
- QC = *Quantity of Chemical*. Total amount of a specific chemical used in new flooding fire extinguishing equipment in a given year, j, by weight.
- $\sum QC_i$ = *Sum of Quantity of Chemical over Multiple Years*. Total amount of a specific chemical used in new flooding fire extinguishing equipment from year (j-15) to year j, by weight.

Foam Blowing

Foams are given emission profiles depending on the foam type (open cell or closed cell). Emissions for open cell foams are assumed to be 100 percent in the year of manufacture (Equation 8). Closed cell foams were assumed to emit a portion of total HFC or PFC use upon manufacture, a portion at a constant rate over the lifetime of the foam, and a portion at disposal (Equation 9).

(i) Open-Cell Foam

$$E = QC$$

Eq. 8

Where:

- E = *Emissions*. Total emissions of a specific chemical in a given year for open-cell foam blowing, in metric tons.
- QC = *Quantity of Chemical*. Total amount of a specific chemical used for open-cell foam blowing in the same given year, in metric tons.

(ii) Closed-Cell Foam

$$E = \sum (EF_i * QC_i) \text{ Where, } i = (j-x) \text{ to } j, \text{ and } x = \text{foam lifetime}$$

Eq. 9

Where:

- j = Index of the given year.
- E = *Emissions*. Total emissions of a specific chemical in a given year for closed-cell foam blowing, by weight.
- EF = *Emission Factor*. Percent of foam's original charge emitted in year j . This emission factor is generally variable, with a separate value for manufacturing, lifetime, and disposal emissions.
- QC = *Quantity of Chemical*. Total amount of a specific chemical used in closed-cell foams manufactured in a given year, j .

Sterilization

For sterilization applications, all chemicals that are used in the equipment in any given year are assumed to be emitted in that year, as shown in Equation 10.

$$E = QC$$

Eq. 10

Where:

- E = *Emissions*. Total emissions of a specific chemical in a given year from use in sterilization equipment, by weight.
- QC = *Quantity of Chemical*. Total quantity of a specific chemical contained in sterilization equipment used in the same given year, by weight.

C. Model Output

By repeating these calculations from the years 1985-2030, the Vintaging model creates annual profiles of use and emissions for ODS and ODS substitutes. The results can be shown for each year in two ways: 1) on a chemical-by-chemical basis, summed across the end-uses, or, 2) on an end-use basis. Values for use and emissions are calculated both in metric tons and in million metric tons of carbon equivalents (MMTCE). The conversion of metric tons of chemical to MMTCE is accomplished through a linear scaling of tonnage by the global warming potential (GWP) of each chemical. The GWP values that are used in the model correspond to those published in the IPCC Third Assessment Report.

Throughout its development, the Vintaging model has undergone annual modifications. As new or more accurate information becomes available, the model is adjusted in such a way that both its projections and its hindcasts are often altered.

For further clarification, additional documents or other information please write to:

Alicia Karspeck
Alternatives and Emissions Reduction Branch
Global Programs Division
Environmental Protection Agency
Mail Code 6205J
401 M Street, NW
Washington, DC 20460

Appendix B. List of Abbreviations

\$/TCE	Dollars per Metric Ton of Carbon Equivalent
AE	Anode Effect
CAAA	Clean Air Act Amendments of 1990
CBM	Chlorobromomethane
CCAP	Climate Change Action Plan
CFC	Chlorofluorocarbon
COP	Coefficient of Performance
CVD	Chemical Vapor Deposition
DPI	Dry Powder Inhaler
DX	Direct Expansion
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
fab	Fabrication Facility
GIS	Gas-Insulated Substation
GWP	Global Warming Potential
HBFC	Hydrobromofluorocarbon
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFE	Hydrofluoroether
HVAC	Heating, Ventilation, and Air-Conditioning
IMC	In-Mold Coating
kg	Kilogram
kWh	Kilowatt Hour
LCCP	Life Cycle Climate Performance
LCD	Liquid Carbon Dioxide
MAC	Marginal Abatement Curve
MDI	Metered Dose Inhaler
MMTCE	Million Metric Tons of Carbon Equivalent
MOU	Memorandum of Understanding
MTCE	Metric Ton of Carbon Equivalent
NFPA	National Fire Protection Association
NIK	Not-in-Kind
nPB	n-Propyl Bromide
NPV	Net Present Value
O&M	Operation and Maintenance
ODP	Ozone Depleting Potential
ODS	Ozone Depleting Substance
OMB	Office of Management and Budget
PCB	Printed Circuit Board
PFC	Perfluorocarbon
PFPE	Perfluoropolyether
R&D	Research and Development
SNAP	Significant New Alternatives Policy Program

SOLAS	Safety of Life at Sea (International Maritime Organization)
TCE	Metric Ton of Carbon Equivalent
VAIP	Voluntary Aluminum Industry Partnership
VOC	Volatile Organic Compound
XPS	Extruded Polystyrene